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A SYSTEMS ENGINEERING BASED METHODOLOGY FOR ANALYZING HUMAN ELECTROCORTICAL RESPONSES (U)

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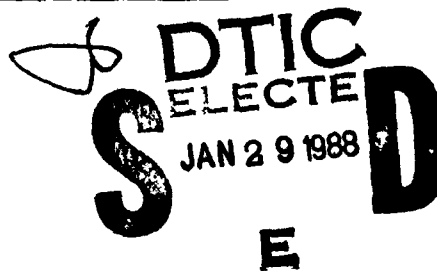**ARMSTRONG AEROSPACE MEDICAL RESEARCH LABORATORY**

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TECHNICAL REVIEW AND APPROVAL

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Armstrong Aerospace Medical Research Laboratory

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The objective of this work was to develop a systems engineering based methodology for identifying and modeling effects of cognitive loading on human electrocortical responses in systems engineering terms. The visual-cortical response was selected as the input-output model around which the methodology was developed. A steady-state input (a continuous sum of sine waves) and a transient input (a train of pulses) were used for system stimulation. Human occipital EEG (surface electrodes at Oz and mastoids) was used as the cortical output. Analysis of input stimuli and output EEG potentials produced human visual-cortical describing functions (gain and phase) and remnant spectra (background EEG).

A stimulus parametric investigation indicated that sensitivity to stimulus modulation depth is unequal across frequencies, and that relatively low stimulus intensity and depth of modulation are desirable to reduce response saturation.

Comparisons between transient and steady-state stimulation revealed that both forms elicited functionally related responses, suggesting that the visual-cortical response

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contains a measurable linear portion. Time domain amplitude changes corresponded to transient and steady-state gain changes.

Consistent trends observed among subjects indicated that it is advisable to group subjects into two classes: alpha responders, and non-alpha responders. Classification would be based upon alpha band (8 to 12 Hz) responses in both remnant and gain curves.

To investigate cognitive loading effects three tasks were utilized: manual tracking, grammatical reasoning, and supervisory control. Changes in visual-cortical response measures related to task loading were observed. With increased cognitive loading, alpha responders generally showed reductions in alpha band gain and remnant, and increases in beta band gain. Non-alpha responders showed increases in beta band gain only. Performance of supervisory control caused a reduction in phase lag for all subjects tested. Results revealed that individual differences must be accounted for.

Some success in matching data with the model forms considered was achieved. Multipath modeling provided a promising approach for handling observed breakout points in the data. Model parameter values were found to relate to task performance scores. A model form based upon alpha and non-alpha classification should be individually applied.

PREFACE

The research summarized in this report was perfromed at
the Armstrong Aerospace Medical Research Laboratory under
Work Units 2312V222 and 718414D1 by Dr. Andrew M. Junker. As
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1. INTRODUCTION

1.1 Objective

The objective of this work was to create a systems engineering based methodology with which to study human brain function. Achievement of this objective would contribute to the present and future condition of this area of research in a number of ways:

* Application of this methodology would provide ways to approach classification of brain responses of subjects and correlation of these responses with facility for performing various tasks.

* This methodology would lead to parsimonious expressions of human brain function (i.e., data compression) in terms of systems engineering models.

* In workload research, a major concern is designing machines to match human capabilites and limitations. Machine characterizations are in systems engineering terms. If brain function could also be character- ized in systems engineering terms, issues of mental workload for systems design could be approached in a more compatible manner.

* This methodology would provide a foundation from which modeling can be accomplished, leading to adaptive on-line models for providing continuous measures of human attention.

* The methodology would be useful for guiding future research, as models could provide a predictive

capability for experimental design, improving the efficiency of the investigative process.

* In the opinion of the authors, one of the biggest flaws in the area of EEG research is the open-loop nature of the electrocortical signals being analyzed, which leads to relatively large trial-to-trial response variability and relative insensitivity of this response pattern to environmental variables of interest. Significant improvement in this regard is likely to reguire some form of loop closure. Efforts to achieve loop closure will be facilitated if the brain function channel is first characterized using systems engineering based methods.

* Loop closure will lead to brain actuated controls.

1.2 Approach

Developing a methodology with which to investigate a system must follow a number of logical steps. First, selection of relevant inputs and outputs must be made, allowing quantitative performance measures of the system under investigation. Effective stimulus parameter values must be determined. An appropriate and sensitive method of analysis has to be chosen. Then, ways in which the input/output measurements vary with changes of internal state can be investigated. Finally, mathematical models of the system, based upon input-output measurements, can be generated.

The visual-cortical response channel input and output were chosen as relevant signals with which to develop the systems based methodology. This was done for a number of reasons. The ElectroEncepholoGram (EEG) was available as a measure of the output of the visual-cortical response. The EEG is relatively "easy" to measure and potentially reflects the occurring underlying brain processes (John, 1977, Lerner, 1984). The visual modality was chosen as the input because light stimulation is easy to manipulate. In addition, considerable work has been done by other researchers using this modality to explore relationships between light stimulation and EEG potentials (Regan, 1972, Spekreijse, 1966, Wilson and O'Donnell, 1980).

What makes the work presented here unique from other EEG research is that it develops a technique to evoke a brain response from a continuously presented sum of ten sine waves. The sum-of-sines input was used to modulate light which in turn evoked visual-cortical responses.

The method of analysis selected for this work was based upon previous research (Junker and Levison, 1980). The earlier work involved measuring human performance in closed loop tracking scenarios and then computing input-output relationships from collected data. Stimulation of the human was accomplished through the introduction of a sum-of-sines disturbance to the closed-loop system. Input-output describing functions and remnant spectra were computed. Describing functions are measures of the linear

gain and phase relationships that exist between inputs and outputs of a system. Remnant spectra are measures of output power not linearly related to system inputs.

Use of sum-of-sines inputs has become standard practice in laboratory manual control studies and has also had application to studies performed in aircraft simulators and to inflight studies as well (Levison and Junker, 1978, Levison, 1971, Levison et al., 1971). Simply stated, this technique involves stimulating or driving the system under investigation with a stimulus consisting of energy concentrated at specific frequencies. These input frequencies are selected in such a manner as to allow the identification of both linear and nonlinear (through analysis of harmonics) input/output relationships. Concentrating input power at specific frequencies also allows analysis of remnant power spectra. Remnant spectra are average measures of power in frequency bands adjacent to, but not including, locations where linear responses to input stimulation are expected.

This method of stimulation, with a continuous set of sinusoids, is referred to as steady-state stimulation. In the case of the human visual-cortical system, exposure to the continuously evoking stimulus causes entrainment to the various frequencies contained in the input stimulus. Once initial start up phenomena subside, the system reaches a steady level of entrainment (Regan, 1979). By concentrating input power at relatively few frequencies, one is able to

maximize the bandwidth over which input-correlated response behavior can be distinguished from remnant-related response behavior.

Transient stimulation was also utilized in this study to analyze the visual-cortical response. Transient stimulation involves stimulating a system with a large amplitude short duration input pulse and observing the evoked response of the system over time. Actually a series of pulses, where between pulses the system was allowed to return to its resting state, was used. The pulse responses were time-lock averaged. In time-lock averaging, each transient response is averaged with each preceding transient response.

If a system under investigation is a purely linear stable system (stimulus power at a given frequency produces a response only at that frequency), transient and steady-state system responses will yield the same information. Both methods were utilized in this study to evaluate the degree of linearity of the human visual-cortical response. The question of linearity is of concern in the application of analysis techniques as the interpretation and modeling of results are affected by the degree of linearity possessed by the system under investigation.

1.3 Organization of this Report

Section 2 provides a discussion of previous EEG research relevant to the work presented here. The developed methodology utilized in this report is presented in Section 3. Sections 4, 5, and 6 provide detailed results of the

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experimental investigation and modeling effort. Therefore it is suggested that the interested reader first read the summary of results found in Sections 7.1 through 7.4, to obtain an overview of Sections 4, 5, and 6.

In Section 4 an investigation into the effects of two parameters which determine the energy of the visual stimuli: average light intensity, and depth of modulation (the amount of modulation about the average) was performed. Measurements resulting from both steady-state and transient stimulation are also presented in Section 4, where comparisons of the outputs are discussed.

Three computer-based tasks were utilized in this study to provide different levels of cognitive loading during visual-cortical response measurement. The tasks were: manual tracking, supervisory control, and grammatical reasoning. These three tasks were chosen because each one required different visual-motor activity. The ways in which the three tasks affect the visual-cortical response are presented in Section 5. Two levels of task difficulty were utilized for the supervisory control task. EEG results for the two levels are also given in Section 5.

The measurements obtained in this work were collected so that they could be used for descriptive input-output modeling. Using the visual-cortical frequency measures, a number of model forms were investigated for their ability to describe and predict the important system characteristics. The results of these modeling efforts are presented in

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Section 6. Models tested ranged from a fourth order-transport lag transfer function to a simp'e gain-transport lag function.

The report concludes with a discussion of the contributions made by realization of the objective of a developed methodology for analyzing human brain function. Findings obtained from this work are summarized to indicate the strengths and weaknesses of the ethodology. Future research possibilites including loop-closure of the visual cortical channel are presented.

2. BACKGROUND

Electoencephalography, or EEG, is a technique for
recording (over time) variations in the electrical potentials
observed from electrodes on the scalp compared either to each
other or to an indifferent or reference electrode elsewhere
on the body. From these electrodes a continuously fluctuating
voltage may be observed. The fluctuations are often periodic
and may take several forms. Some of these patterns are so
reliable that they have been identified by Greek letters and
may be expected to occur periodically in the normal brain
(Berger, 1929).

Rhythmic variations are continually present at the
surface of the scalp from well before birth to death. The
various frequencies and distributions of specific patterns
of the EEG wax and wane, providing the brain researcher
and clinician with constant records of the changing patterns
of electrical activity of the brain. These continual patterns
are called spontaneous encephalograms, to distinguish them
from discrete EEG waveforms that either follow stimulation or
precede and accompany action.

2 1 Some History

Berger's early work (1929) has important implica-
tions to work reported in this thesis. He showed that the
EEG consisted of "alpha spindles", trains of alpha waves
(rhythmic waves occurring at a frequency between 8 and 13

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hz) with beta waves (greater than 13 hz) superimposed. He asserted that with "strenuous mental effort" the relative number of alpha spindles are reduced in proportion to the number of beta waves. He detected suppression of the alpha spindles -"desynchronization"- under circumstances such as eyes open, reading, mental task performance, tactile stimulation of the hand, presentation of sound stimuli, and hearing instructions to perform a particular movement (but no suppression necessarily accompanying the movement itself). He ascribed this suppression phenomenon to the participant's directing his or her attention toward the stimulus or task, with the return of the alpha spindles being an indicator of undirected attention. He also demonstrated EEG evidence of habituation as the alpha spindles spontaneously returned during successive stimuli.

Berger also noted changes in wave amplitude but was primarily concerned with the duration and latency of onset or suppression of alpha spindles. He postulated that the waxing and waning of alpha spindles during mental activity represented the "resting" and information-processing acti-vity of the cerebral cortex, which was thought to occur in 1/2 to 2 second cycles. He considered beta waves as indications of cortical activity during mentation.

The confirmation of these findings by other research-ers in the 1930s and 1940s (Walter, 1953) and the subse-quent extension of them by Berger was greeted with great excitement by the neurophysiology communities, for it was

assumed that these potentials were summated cortical spike
activity and that the EEG was therefore like a window
on the brain through which one could view such activity.
It was plausible to interpret low-frequency, high-
amplitude waves as being summated synchronous unit
activity, and high-frequency, low-amplitude waves as being
summated desynchronous unit activity from neuronal firing.
As it turned out, this was a misinterpretation.
Nevertheless, within this general framework of regarding
the EEG as a mirror of unit activity, considerable effort
was expended during the following years in attempting to
identify new waveforms and to correlate these with various
behavioral states.

Lindsley (1952) presented what many have considered
to be the first and most successful characterization of
the relation between the EEG, behavioral efficiency and
awareness, set against an eight-category continuum of
behavior stretching from strong, excited emotion through
to coma and death. He pointed out that the alpha rhythm
and conditions which promote its amplitude and frequency
of appearance are largely associated with conditions of
relaxation and quiet.

Some authors have been very persistent in the view
that what is measured in the EEG is an artifact of psycho-
logically trivial and almost mechanical aspects of the
brain. For example Kennedy (1959) claimed that one could
replicate certain brain rhythms by mechanical pulsation of

gel within an appropriately shaped vessel. Lippold and Novotny (1970) claimed they had demonstrated, in experiments (which others have found difficult to replicate) that the occipital alpha, as measured at the rear of the scalp, is merely a reflection of electrical activity produced by tremor of the extraocular muscles. Their data have been challenged on the basis of data from subjects who have no eyeballs, on the fact that occipital alpha can be shown to vary systematically under auditory stimulation, that subjects with eyes open show systematic variation in the EEG which relates to aspects of performance, and by evidence of subcortical pacemakers, which cause both tremor and EEG oscillations (Gale and Edwards, 1983). Whatever predisposition there is in the cortical mass to oscillate at particular frequencies, similar oscillations have been detected in lower brain centers which are thought by some authorities to be the principal source of activity at the cortex (Andersen and Andersson, 1968).

2.2 Physiological Basis of the EEG

What is the source of these recurring rhythmic potentials and event-related potentials measureable at the surface of the scalp? The discharge of a single neuron or single nerve fiber in the brain cannot be recorded from the surface of the head. Instead, for an electrical potential to be recorded all the way through the skull, large portions of nervous tissue must emit electrical

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current simultaneously. There are two ways in which this can occur. First, tremendous numbers of nerve fibers can discharge in synchrony with each other, thereby generating very strong electrical currents. Second, large numbers of neurons can produce dendritic-like electrotonic conduction, though not emit action potentials. This electrotonic conduction can give prolonged periods of current flow that can undulate slowly with changing degrees of excitability of the neurons. Simultaneous electrical measurements within the brain while recording brain waves from the scalp indicate that it is the second of these that causes the usual brain waves (Elul, 1972).

The surface of the cerebral cortex is composed almost entirely of a mat of dendrites from neuronal cells in the lower layers of the cortex. When signals impinge on these dendrites, they become partially depolarized, emitting negative potentials characteristic of excitatory post-synaptic potentials (Guyton, 1976). Elul concluded that synaptic functional units are the generators of the EEG waveforms. A "synaptic functional unit" is "a group of synapses sharing the same presynaptic input" (Elul, 1972). Such units would consist of thousands of synapses which, because of shared presynaptic input, would be polarized or hyperpolarized together. Although it has been calculated that relatively small numbers of synaptic units could generate the potentials observed at the surface, it is necessary to hypothesize that different groups of

generators take over the generating function several times each second in order to explain the different time course of cortical cells and surface waveforms. Thus, "it may be concluded that the origins of the EEG are periodic variations of synaptic and dendrite potentials of groups of cortical neurons" (Stern et. al., 1980).

Where a large group of cortical neurons is driven by identifiable volleys of afferent neural activity, as in the case of evoked potentials, the genesis of surface recorded waves is easily understood in terms of the mechanisms just described. But in the case of spontaneous rhythms, it is not at all obvious why the dendrites and synaptic connections of large groups of cortical neurons would vary in synchrony. What, for example, is the genesis of the alpha rhythm? While no firm answer can yet be given, it is probably that subcortical brain structures, particularly the thalamus, provide sychronizing signals to broad cortical areas. Brain stem mechanisms have also been shown to control some aspects of the EEG. Ascending discharges from the reticular formation cause a shift from alpha and slower rhythms to faster, less synchronized waves in cortical EEGs. There is a general relationship between the activity in the cerebrum and the average frequency of the EEG rhythm, the frequency increasing with higher and higher degrees of activity. Delta waves (frequencies below 3.5Hz) are observed in stupor, surgical anesthesia, and sleep; theta waves (between 4 and 7Hz) in

psychomotor states, in infants, and in highly coherent transcendental meditative states; alpha waves (8 to 13Hz) during relaxed states; and beta waves (above 14Hz, and as high as 30Hz) during periods of intense mental activity. In addition, during periods of mental activity the waves usually become asynchronous rather than synchronous so that the voltage falls considerably, despite increased cortical activity (Guyton, 1976).

Traditionally, the human brain has been seen as a vast switching network consisting of tens of billions of individual processing cells, neurons, communicating with one another through electrical impulses (Wiesel, 1967). Since the early 1970s, however, a group of neuroscientists has challenged this model in favor of one that emphasizes neurons working together in large groups and interacting with complex electromagnetic fields that pervade the brain (Lerner, 1984).

According to this new model, known as Cooperative Action, thoughts and perceptions are encoded in the changing patterns of electromagnetic fields rather than in the impulses of individual neurons. Moreover, the fields generated by the synchronous activity of thousands or millions of neurons are continually reflected back on the neurons themselves and in turn influence their activity (John, 1977). Surface EEG recordings may reflect this underlying synchronous activity, suggesting that analysis of the frequency content of the EEG is appropriate.

2.3 Spontaneous EEG

The measurement of spontaneous or ongoing EEG signals in the clinical setting has been quite beneficial. Early studies (Gibbs et al, 1935; Walter, 1936) showed records of this activity to be a useful aid in the diagnosis of epilepsy and cerebral tumors. Today EEG tests routinely provide information pertinent to the diagnosis and treatment of these and other abnormal conditions including cerebral trauma and thrombosis, developmental abnormalities, and metabolic and endocrine disorders. It is also used to monitor sleep, depth of anesthesia, and cessation of brain function (Gevins and Schaffer, 1980).

It would seem that the spontaneous EEG would be useful for detecting cortical activity changes associated with performance of "cognitive" tasks since it measures the presumed "site" of cognition. Researchers have considered various aspects of the EEG including the microwave frequency range (Tourrine, 1984) as indicators of cognition. As pointed out by Gevins and Schaffer (1980), "other techniques have been more successfully related to cognitive operations than continuous EEG activity". They present some of the theoretical considerations and practical requirements which have limited the success in relating EEG measures to cognition. Gevins and Schaffer (1980) also point out that character-

istics of the EEG such as absolute amplitude in microvolts vary greatly among individuals. Also that mental activity accompanying a "baseline" is unknown, and can be assumed to be quite variable. This suggests therefore, that it is useful to compare EEG measurements between two or more tasks, and that the tasks should exclusively represent different levels of the investigated cognitive activity. With these and other considerations noted, they go on to present a critical review of recent investigations of the relationship between EEG changes and higher cortical functions. Some of the effects cited include: decrease in alpha and an increase in beta activity with cognitive loading (Gevins et. al., 1979), alpha decrease during a visual discrimination task (Stigsby et. al., 1977), alpha and beta integrated voltage decreases as the complexity of a visual image increases (Gale and associates, 1969, 1971), more complex stimulus patterns evoke longer lasting desynchronization (Berlyne and McDonnell, 1965), increased alpha activity is associated with decreased arousal (Surwillo, 1963), and occipital alpha is inversely correlated with the number of difficult subtractions performed (Vogel et. al., 1968). Both Gevins and Schaffer (1980), and Gale and Edwards (1983) state that no conclusive relationship has been found between the EEG and the general level of intelligence. Gevins and Schaffer make the strong statement that "no experiment has yet demonstrated specific EEG changes that could be

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unequivocally related to information-processing aspects of task performance as opposed to oculomotor and limb movement or arousal-related changes". After considering a number of studies dealing with EEG correlates of higher cortical functions, Gevins and Schaffer conclude that "little fundamental knowledge has been uncovered and that Berger's observations thus remain largely unelaborated".

2.4 Evoked Potentials

A second type of slow-wave potential, referred to as the evoked potential (EP) can also be observed. In common with the spontaneous EEG, evoked potentials are recordings of voltage changes from relatively large areas of the nervous system. But in contrast to the spontaneous EEG, evoked potentials are voltage fluctuations that are time-locked to the presentation of some stimulus, such as light, sound, or electrical stimulation of some nucleus or fiber tract. They are potentials evoked by a stimulus and bear some fixed time relation to the presentation of the stimulus. In   case of the visual system, a transient response to a lash of light usually ends within a second Thus a respons to a train of pulses, where each pulse follows each o_her at sufficiently long intervals that the system returns to its initial state before the next pulse occurs is called a Transient Evoked Potential (TEP) (Donchin, 1966). When stimuli are delivered at a greater rate, so that the response to a stimulus has not died away

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before the next stimulus occurs, the response is called
a Steady-State Evoked Potential (SSEP) (Regan, 1979).

The technology developed in this thesis is for
analysis of visually evoked potentials, both steady-state
and transient. Thus literature relating mainly to
visually evoked response work is considered.

2.4.1 Steady State Evoked Potentials

In the case of the SSEP, the evoking stimulus is a
continuous periodic function. The ensuing EEG is recorded
continuously throughout stimulus presentation and then
subsequently broken down into its spectral components via
a frequency transformation technique. In general, the
spectrum appears as it would if it were simply the
spontaneous EEG spectrum, with the addition of pronounced
peaks at the frequencies of the eliciting stimulus.

Spekreijse (1966) investigated the visual SSEP by
utilising a technique of time averaging, using a Computer
of Average Transients locked to the periodic stimulus, and
thus derived his frequency response information from wave
shapes in the time domain. Spekreijse's data for two sub-
jects are reproduced in Figure 2.1. The data was obtained
by stimulating one frequency at a time and, from time
locked averages, computing gain and phase values. The
data illustrate the 10 Hz alpha resonance characteristic.
In this resonance region the fast amplitude variation is
coupled to a phase step. For one subject Spekreijse found

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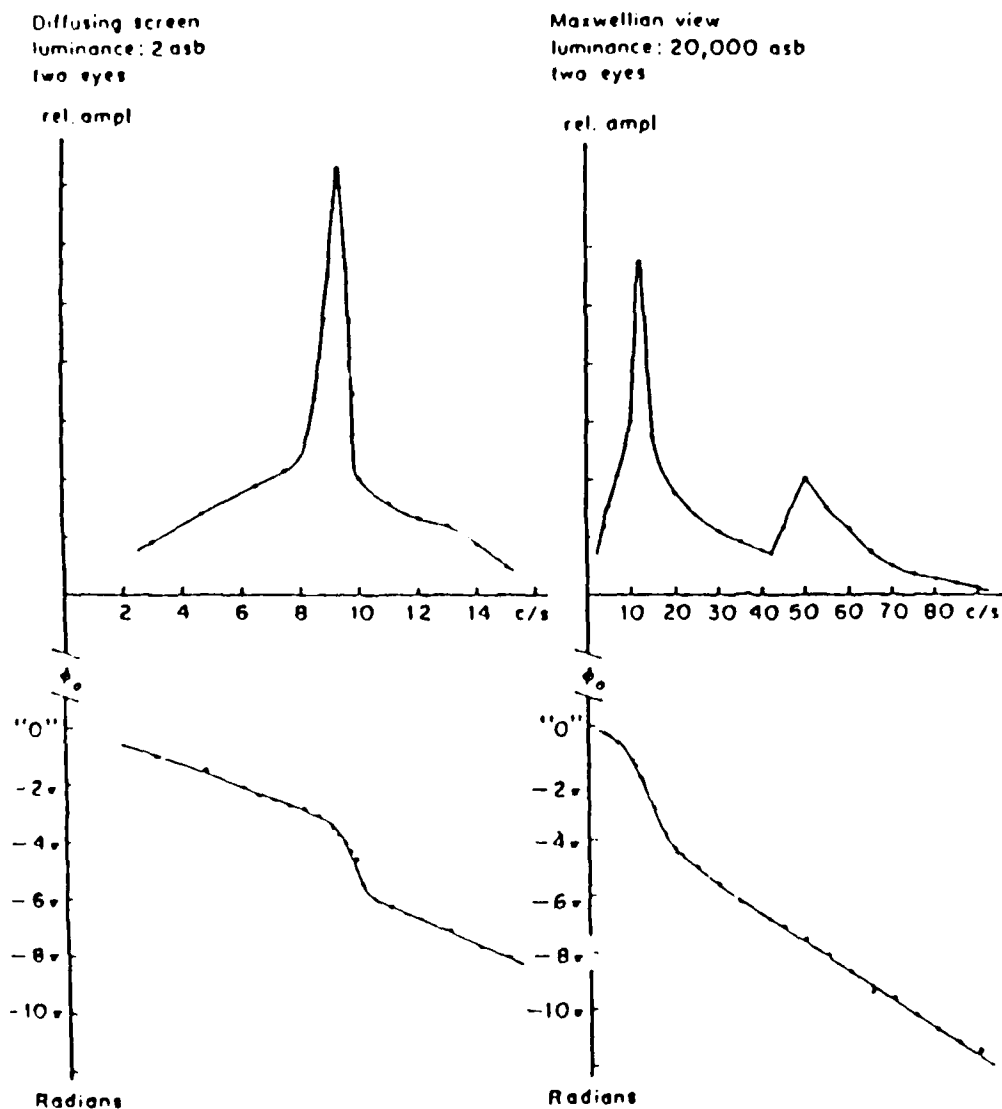
Figure 2.1. Amplitude and phase characteristics for two subjects with sinusoidally modulated light; the frequency scale is linear; amplitudes in relative units. Both subjects exhibit large alpha activity (From Spereijse 1966).

this phase shift to be as much as 720 degrees at 10 Hz.

Researchers have found that the alpha resonance varies from subject to subject, but corresponds closely with the alpha frequency of subject's spontaneous EEG. In addition, the sharpness (Q factor) and amplitude of the SSEP peak also show close correspondence with the sharpness of tuning and amplitude of spontaneous alpha activity. Regan (1972, p77) reports that they appear to be independent and to a first approximation sum linearly.

Spekreijse found that SSEPs show a high percentage of second harmonic distortion which could not be reduced by reducing the modulation depth of the signal. This indicated the presence of an essential nonlinearity. This type of nonlinearity arises when there is a discontinuity or a parabolic nonlinearity in the characteristic curve of the input-output relationship (Regan, 1972, p49). He observed this essential ('nonanalytic') nonlinearity principally for sinusoidal inputs below 9 Hz and above 15 Hz. This nonlinearity was more prominent for subjects exhibiting high alpha resonance in their spontaneous EEG.

By adding a second 'linearizing' signal (sine wave, square wave, or gaussian noise) to his stimulating sinusoid, Spekreijse found that the amplitude of the fundamental was little affected by the addition of the auxiliary signal, whereas the second harmonic component was very much reduced. For one of his linearizing signals, Spekreijse chose a 20 Hz square wave with the

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same amplitude as that of his sinusoidal input signals.
The linearizing signal was chosen to be uncorrelated with
the frequencies of the sinusoidal input signals so as to
have no harmonic interactions. By making use of this
property, Spekreijse was able to 'dissect out' a function-
al sequence of stages of information processing for the
visual SSEP system. His findings led to the suggestion of
a simple serial processing model for evoked responses
below 30 Hz, and another for high frequencies (45-60 Hz).

Spekreijse has continued to use his linearizing
approach for such things as diagnosis of multiple
sclerosis (Duwaer and Spekreijse, 1978). He investigated
other techniques for quantifying the systems attributes of
the visual evoked potential system in man and concluded
that his linearizing technique was superior (Spekreijse
and Reits, 1982). Included in that work was the
application of a Wiener Kernel approach.

A second researcher who has made significant
contributions to the development of steady-state evoked
potential technology is Regan (1972). For his earlier
work Regan (1966) devised an analog Fourier analyzer to
look at magnitude and phase of SSEPs. He found the
largest peak response in the 10 Hz range with an
additional peak at approximately 16 Hz. Associated with
the amplitude peaking was a slight phase jump. His mea-
surements were averaged over 20 second periods. When he
attempted the same measurements over 7 second periods he

found his measurements were unstable. He found that phase measures were more repeatable than amplitude measures.

As mentioned above, Spekreijse proposed a model for the long latency portion of the SSEP (below 30 Hz) and for high frequency flicker (45-60 Hz). Regan (1970) suggested that third parallel model was needed for the 16-18 Hz region. Thus he proposed three frequency regions: a low, medium, and high (refer to Figure 2.2). Regan (1977) concluded that EPs generated in these three ranges seem to come from different parts of the cortex. He stated for example "in multiple sclerosis patients, medium-frequency flicker EPs are delayed, whereas high-frequency responses are not". Unlike the alpha region, the medium frequency region seemed to be influenced by the color of the stimulus and its topographical distribution differed from the distributions of the other components (Regan, 1977).

Regan (1976) devised a simultaneous stimulation technique to investigate SSEP latency in which his stimulus contained three sine waves. He found it could reduce the measurement variance and improve precision by about four times when determining SSEP latency.

The medium EP frequency response range (16-18 Hz) is in the same range as the beta region of the EEG spectrum. Researchers have reported spontaneous EEG beta changes with cortical activity shifts (Gevins et. al., 1979). Of interest therefore, will be how evoked responses in this region also show sensitivity to cortical activity.
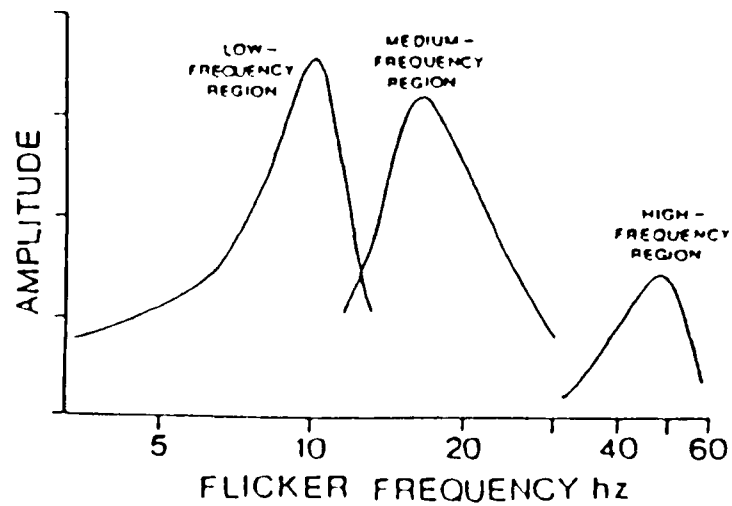
Figure 2.2. Effects of stimulus frequency upon flicker
EPs. EPs were elicited by a spatially
unpatterned (blank) flickering patch of
light. (From Regan 1975).

Based upon the findings of Regan and others, Wilson and O'Donnell (1980) began to investigate the feasibility of using the SSEP as a measure of task difficulty. Wilson (1980) reported effects of visual tracking task difficulty on the SSEP. Increasing difficulty levels of tracking were associated with greater amounts of phase lag of high frequency SSEPs (above 40 Hz.). Phase lag and amplitude of medium frequency SSEPs were unaffected.

2.4.2 Transient Evoked Potentials

The transient EEG response is commonly referred to as an event related brain potential. The event related potential represents the brain's response, via voltage fluctuations, to some discrete stimulus or cognitive event. Typically, these fluctuations have a duration of 600 milliseconds or more. These fluctuations or deflections, which occur at relatively consistent temporal intervals, are called components (refer to Figure 2.3).

Establishing the relationship between the parameters of TEP components (i. e., amplitude and latency) and the independent variables encompassed in the eliciting stimulus is the nucleus of basic TEP research. This analysis is aided by the use of a statistical technique, which has been adapted by Donchin and his colleagues (1979, 1966), known as principal component analysis (PCA). Basically, a PCA converts each recorded TEP from time

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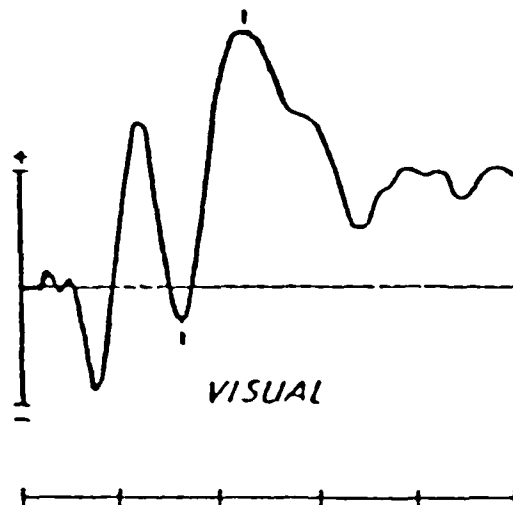
VISUAL

Figure 2.3.   Averaged visual evoked response recorded from
               eight subjects. The tracing is the computer
               average of 4,800 individual responses. The
               amplitude calibration indicated on the left
               of each tracing is 10 microvolts, the time
               calibration is 100 msec/div indicated at the
               bottom of the diagram. Negative voltages are
               represented by downward deflections.
               (From H. G. Vaughan, Jr., 1969)

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series data into a vector comprised of specific orthogonal components. Thus a PCA allows researchers to isolate and quantify specific TEP components.

Components are catalogued or labeled using the following terminology. Those comprised of a positive voltage fluctuation are labeled with a "P"; negative fluctuations with an "N". This prefix is then followed by a number which indicates the minimal latency (as measured from the time of the eliciting stimulus) at which the component appears. For example, P300 represents a positive voltage fluctuation which occurs at least 300 milliseconds after the discrete event that elicited the TEP. The amplitude of P300 has been shown to be inversely related to the perceptual-central processing demands imposed on the operator (Isreal et. al., 1979, Wickens et. al., 1977). Similarly, N100 is negative fluctuation occurring at least 100 milliseconds after the evoking stimulus occurrence. It has been shown that the N100 amplitude is directly related to stimulus relevancy or the amount of attention focused on the eliciting stimulus (Hillyard and Picton, 1979, Naatanen and Michie, 1979, Hansen and Hillyard, 1983). Naaten and Gaillard (1983) have shown that the N100 and especially the N200 components of the human TEP show an enhancement in amplitude from selective attention. Inattention, either by distraction or habituation, reduces N100-N200 amplitudes.

3. METHODOLOGY

To successfully provide evoking stimuli and analyze
the resulting data required development of a stimulus
apparatus and computer programs with which to collect and
analyze evoked potential (EP) recordings. This section
discusses this developed methodology.

3.1 Apparatus

Light (as opposed to sound etc.) was chosen as the
evoking stimulus for two reasons. Light stimulation was
previously used in the laboratory where the work was to be
done, thus a high quality light driver or stimulator and a
light sensor were available. It was easy to achieve a
reasonably linear summation of several sine waves in the
form of amplitude-modulated ("flickering") light.

In addition to the flickering lights, a video display
was used to present computer generated cognitive loading
tasks to be performed by the subjects. Initially the
flickering light stimulation was provided by two
fluorescent tubes 26 cm long, mounted on each side of the
display terminal. Preliminary results indicated that the
evoked response was not reliable for this configuration.
The best evoked response was achieved when the two images,
the evoking light stimulus and the video display, were
combined. This was accomplished by combining the two
images through an 18 cm x 26 cm half-silvered mirror

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placed at 45 degrees to both images (Figure 3.1). The evoking stimulus was provided by the two fluorescent tubes 26 cm long and mounted 4 cm behind a 25 x 27 cm translucent screen in order to distribute light as evenly as possible across the visual field. Each fluorescent tube measured 10 cm in diameter and exhibited a cool white spectrum. The average intensity of these lights could be varied from 0 to 160 ft-L as measured at the subject viewing point with a photometer.

The signal to the fluorescent tubes was provided by a Scientific Prototype, model GB, tachistiscope/light driver, which was modified so that average intensity and depth of modulation could be adjusted. A United Detector, model PIN 10D, high speed photocell placed at the subject's viewing point was used to record the amplitude of the visual stimulus. Using the photocell to measure generated visual signals, it was determined that the light generation system was linear in amplitude response and produced a flat input/output spectrum up to 500 Hz.

In addition to the image provided by the evoking stimulus, the second image (the video task display) was presented on an Audiometrix 11 in x 11 in video monitor. The advantage of this configuration was that no matter where the participants looked exposure to the evoking stimulus was maintained.
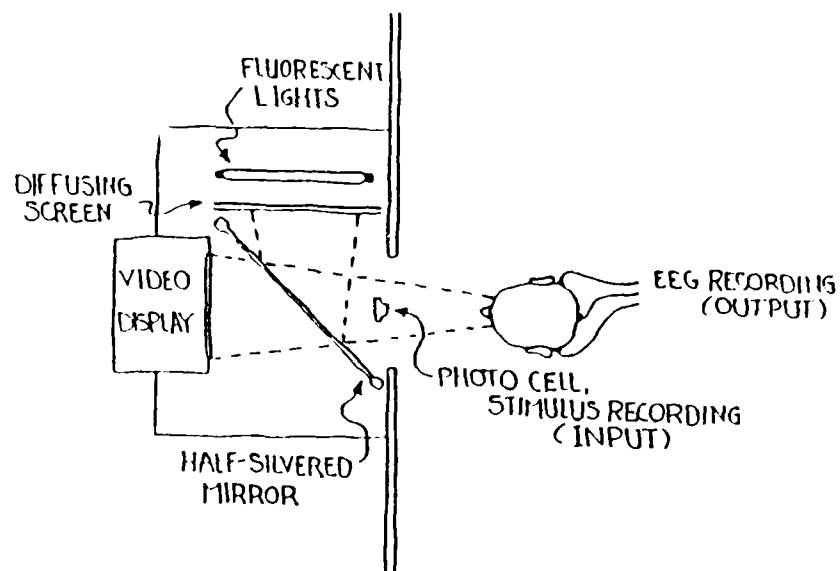
Figure 3.1.   Experimental setup.

3.2 Stimulus Generation

3.2.1 Steady State Stimulation

For this condition sinusoidally modulated light served as the driving stimulus. The lights were modulated using a time history wave composed of 10 harmonically non-related frequencies. The 10 frequencies were harmonics of the fundamental frequency of the data collection process, but were not harmonically related to one another. A Digital Equipment Corp. (DEC) PDP 11/60 was used for stimulus generation. Analysis involved Discrete Fourier Transformation (DFT) of collected time history data. Having all 10 sine waves as multiples of the fundamental frequency insured minimal smearing of the power in the frequency domain.

Initially a Nicolet 660 A dual-channel DFT analyzer was used for frequency analysis. This system provided a frequency resolution of only 0.25 Hz. Results with the Nicolet system indicated that 0.25 Hz resolution was not adequate to separate the evoked response from the background or remnant response. This is discussed in Section 4.1 of this report.

Subsequent analysis was done with a DEC PDP 11/34 computer. Working within the limitations of the available computing power, the finest frequency resolution achievable was 0.0244 Hz using the PDP 11/60 for stimulus generation and data collection and the PDP 11/34 for data

analysis. This was due to the fact that 2048 point DFT transforms were the largest possible, and that a minimum sampling rate of 50 Hz was needed. At a 50 Hz sampling rate, 2048 point transforms provide a time history of 40.96 sec. The fundamental frequency is equal to the inverse of the length of the sampled time history (1/40.96sec =0.0244 Hz). It is the fundamental frequency which determines the frequency resolution of the analyzed data. The 50 Hz sampling rate, coupled with appropriate anti-alias filtering (discussed in Section 3.5), was used to allow investigation of EEG frequencies up to 25 Hz. As indicated in the background section of this report, the alpha and beta frequency bands (between 7 and 23 Hz) showed the most sensitivity to cognitive changes. Therefore, this frequency range was chosen for investigation.

In addition to chosing the frequency values for the Sum-Of-Sines (SOS) input as nonharmonically related to one another, none of the component frequencies contained a sum or difference of any of the other component frequencies. This restriction on the sine wave selection was implemented to avoid possible interactions due to harmonic and first order nonlinear interactions. These requirements were also implemented to set the stage for future investigations of first order nonlinear properties at harmonics and intermodulation frequencies of the input frequencies (Victor and Shapley, 1980). This form of

analysis is beyond the present scope of this effort
however.

As part of the analyses performed for this report,
"remnant" values were computed around the component SOS
frequencies. System response power at non-input
frequencies, in this context, is defined as remnant.
Remnant or background power measurements are average
values of the EEG power about the SOS component
frequencies excluding the power at the actual component
frequencies themselves. These averages were computed from
the EEG data for each of the SOS input frequencies. Ten
values at frequencies above and ten values at frequencies
below each of the input frequencies or a total of 20 power
measurements were used to compute each remnant value
(Junker and Levison, 1980).

Therefore, in addition to the above mentioned
frequency selection requirements, care was taken that none
of the harmonics or sums and differences were within 10
frequency bins of the other selected frequencies. These
requirements were met by selecting the 10 sine waves
through trial and error. The 10 component frequencies
selected, including their harmonic relationship to the
fundamental frequency (0.0244 Hz), are listed in Table 3.1.

To describe a sinewave requires three things:
amplitude, period or frequency, and starting phase value.
For light stimulation a fourth aspect must also be
specified; the offset from zero amplitude. Diffuse light

can only be made brighter or dimmer about some average

illumination. Thus to describe the light properties of a

TABLE 3.1   The 10 SOS frequencies.

FREQUENCY #	FREQUENCY (Hz)	HARMONIC #
1	6.25	256
2	7.73	317
3	9.49	389
4	11.49	471
5	13.25	543
6	14.74	604
7	16.49	676
8	18.25	748
9	20.23	829
10	21.74	891

single sinusoidally modulated light, measures of average

intensity and depth of modulation are used. Average

intensity values of 40 and 80 ft-L were used in the work

presented here. The effects of these two intensity levels

on the SSEP are presented in section 4.2. Depth of

modulation is specified as the percentage of deviation

about the average intensity. An intensity change from off

(no light) to twice the average intensity is equivalent to

100% modulation. SSEPs to modulations as small as 0.6%

have been reported and saturation to single sinewave

stimuli above 30% modulation has been measured

(Spekreijse, 1966). When a sum of 10 sine waves are

combined, specifying the resulting signal depth of

modulation becomes more complex. Due to the way the

sine waves combine, the resulting signal can be considered

pseudo-gaussian or normally distributed. Therefore the

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depth of modulation is related to the variance
or standard deviation of the normal process. The total
power in the 10 sine wave signal (which is equivalent to
the variance of this signal) is given in equation 3.1.

$$\text{Total Power} = \sum_{i=1}^{10} (A_i^2 / 2) \qquad (3.1)$$

$$A_i = \text{Amplitude of ith sine wave}$$

The maximum stimulation possible is 100%. As a design
consideration 3 times the square root of the variance
(sigma) was not to exceed this 100% modulation. Designing
to stay within sigma insured that the signal would not
exceed maximum modulation approximately 99% of the time.
In equation 3.2 it is shown that this translates into an
allowable maximum depth of modulation for each of the 10
sine waves of 14.7%. Two depths of modulation were used
in this report: 6.5% and 13%. The effects of these depths

$$\text{sigma} = 100 / 3 = (10 \, A_{max}^2 / 2)^{1/2}$$

$$(3.2)$$

$$\text{thus, } A_{max} = 14.7\%$$

of modulation on the SSEP are presented in section 4.2.
Equal depths of modulation were utilized for each of the
ten sine waves. It is possible to shape the frequency
spectrum of the stimulus by using different values for
each sine wave. For this beginning work there were no
previous results to suggest that a spectrum with other

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than equal amplitudes would be more effective, thus flat spectra were used (i.e., equal amplitude for each Ai).

For every data collecting trial the starting phase values for each of the 10 component sine waves were randomized with a uniform random number generator, insuring that the time sequence of the flickering light presentation was always random from trial to trial. This procedure was utilized to minimize possible effects due to stimulus habituation.

The sum-of-sines wave was generated with a PDP 11/60 digital computer. The digital signal was converted to an analog signal using an analog to digital (D/A) converter. The digital computer was run at a 50 Hz sampling rate. Thus the analog signal contained zero order stairstep noise at this frequency. The analog signal was filtered using a Kron-Hite model 3750 filter (cutoff at 40 Hz, 0 dB up to 25 Hz, down 3 dB at 40 Hz, 24 dB /Octave rolloff) to eliminate this D/A generated noise. The filtered signal was then fed into the Scientific Prototype, model GB, tachistiscope/light driver.

3.2.2 Transient Stimulation

The Fourier transform of an impulse in the time domain is a flat spectrum in the frequency domain. A pulse in the time domain will provide a band limited flat spectrum in the frequency domain. The steady-state sum-of-sines stimulus used in this work produced a flat

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spectrum in the frequency domain between 6.5 and 21.5 Hz (equal Ai amplitudes). Thus a transient pulse was used which produced a flat spectrum over the same frequency range. This was accomplished by generating a 0.01 sec pulse with the PDP 11/60 computer, passing it through a Kron-Hite model 3750 low pass filter (described in Section 3.2.1) set at 40 Hz cutoff, and sending it to the light driver. The transient stimulus was actually a train of 40 pulses. Interstimulus time was varied between 1.28 and 1.38 sec, the variability (0 to 0.1 sec) was generated with a uniform random number generator for each stimulation segment.

For system identification, one advantage of a steady-state approach over transient is that input power can be concentrated at selected frequency values. In the case of the transient stimulus the power cannot be concentrated at specific frequencies. Therefore it was not possible to achieve the same power levels for the transient stimulus. Pulses were generated with the maximum allowable amplitude possible. This issue is addressed in section 4.4 where transient and steady state comparisons are considered.

3.3 Measurement Techniques

To record EEG signals, Beckman silver/silver chloride electrodes were used with a Grass model P511 AC amplifier (amplification of 50,000 and bandpass 0.1 to 300 Hz). The signal electrode was placed at Oz, the reference

electrode at right mastoid and ground electrode at left mastoid according to the 10-20 International System of electrode placement (Jasper, 1958). This montage was chosen because other results in our laboratory (Wilson 1979) suggested that it would provide the strongest steady-state evoked potentials (SSEP). Since interest was in temporal content more than the spatial attributes of the SSEP, it was decided to stay with this electrode placement. A systematic search for the best electrode montage which yields task sensitive SSEP is warranted, however it was beyond the scope of work presented here. Impedance between electrodes was less than 5 K ohms.

3.4 Cognitive Loading Tasks

Three tasks, requiring various levels of visual, mental, and motor processing, were used to elicit diverse cognitive states with the intention of evoking different visual-cortical responses. These tasks were: manual tracking, supervisory control, and grammatical reasoning. The three tasks were similar in that the input to subjects came from a video display and the output from subjects was by manual operation of a control stick or push-buttons. The tracking task required continuous manual control and little or no conscious decision making once the task had been learned. The grammatical reasoning task required processing of a larger visual scene, which only changed

every few seconds. Subjects were primarily involved in logical processing, followed by simple true/false button responses. Supervisory control required processing of the complete visual scene, which changed continuously. Subjects were engaged in continuous decision making, and rapid discrete actuation of 5 buttons. Including the condition of lights-only, a total of 4 experimental conditions were tested.

For the tracking task, a controlled element of the form $a/(s-a)$, where "a" has a positive real value, was used. This type of system represents a first-order instability, where an initial nonzero system output will grow exponentially with time if the human operator makes no corrective inputs. The rate of error increase, and consequently, the inherent difficulty of the tracking task, increases with increasing 'a'.

In order to provide a well defined tracking task, the system was driven by a first-order external pseudo-random input applied in parallel with the operator's control input (Figure 3.2). The "apparent workload" imposed by this task, then, is influenced by the selection of both the plant instability and the parameters of the tracking input (amplitude and bandwidth). Task parameters were selected on the basis of sensitivity analyses performed previously for the Air Force (Zacharis and Levison, 1979).

The supervisory control task used in this work was developed by Pattipati, Kleinman, and Ephrath (1975). The

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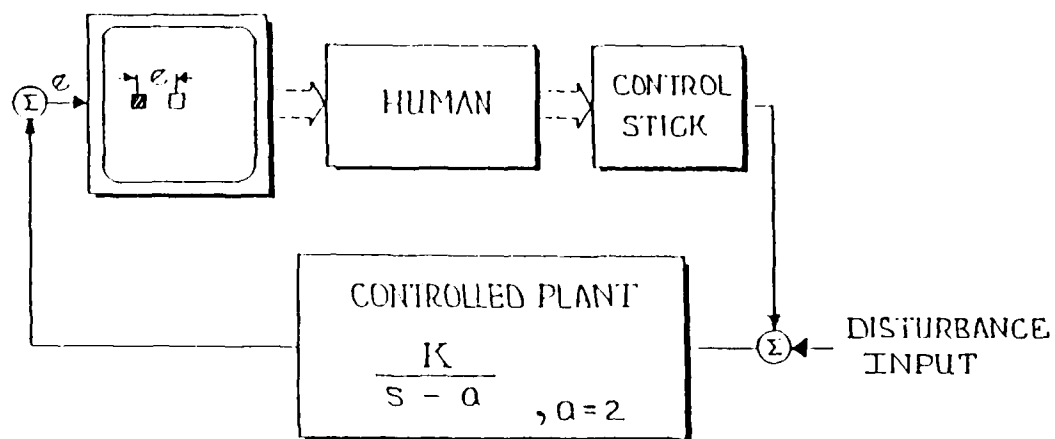
Figure 3.2. Manual tracking task block diagram.

experimental paradigm was a modified version of one used by Tulga (1978). The subjects observed a CRT display on which multiple, concomitant tasks were represented by moving rectangular bars (Figure 3.3). The bars appeared at the left edge of the screen and moved at different velocities to the right, disappearing upon reaching the right edge. Thus, the screen width represented an opportunity window, or the time available (Ta) for the task. At any given time there were, at most, five tasks on the CRT display with a maximum of one on each line.

The height (reward value) of each bar was either one, two, or three units. The number of dots (from 1 to 5) displayed on a bar represented the time required (Tr) to process the task. The subject could process a task by depressing the appropriate push-button as in Figure 3.3. Once a button had been pushed, the computer remained dedicated to that task until task completion or the task ran off the screen. By processing a task successfully, the subject was credited with the corresponding reward, and the completed task was eliminated from the screen.

The supervisory control task, therefore, involved the problem of allocating attention among multiple tasks in a supervisory control system. Two levels of task difficulty were utilized to test task effects on visual-cortical describing functions. In the "easy" condition it was possible to allocate attention successfully among the multiple tasks. In the "hard" condition, the time
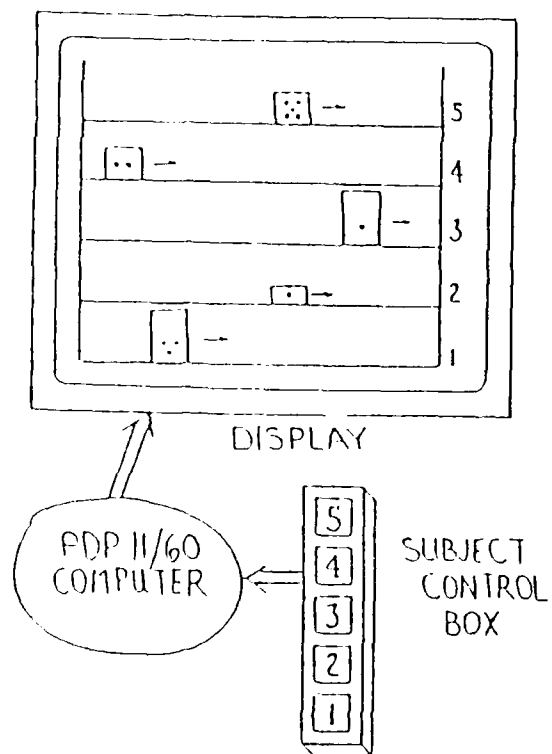
Figure 3.3. Supervisory control task; video display
and subject control box.

required exceeded time available, and it was not possible to complete all allocations successfully. Stated another way, the ratio Tr/Ta was low in the easy condition, and high in the hard condition.

The grammatical reasoning task (Shingledecker et al., 1983) is based on the original grammatical reasoning task developed by Baddeley (1968). The task is designed to impose variable processing demands on resources used for the manipulation of grammatical information. Stimulus items are two sentences of varying syntactic structure accompanied by sets of three symbols (Figure 3.4). The sentences must be analyzed to determine whether they correctly describe the ordering of the characters in the symbol set. This version used two sentence items worded either actively/negatively or passively/positively and described three symbols. This was considered the high demand level. The objective for the subject was to determine whether both sentences matched in their correctness. If both sentences correctly described the ordering of the three symbols, or if neither correctly described the symbols, the appropriate response was positive. If one sentence was correct but the other was not the appropriate response was negative. There was a 7.5 sec time limit for responding. Binary responses were entered manually on two labeled keys, on a four button key board, placed on the right arm of the subject's chair.

For developing a systems based methodology, it was

EXAMPLE:

```
+-------------------------+
|  +-------------------+  |
|  |                   |  |
|  |    * FOLLOWS  #    |  |
|  |    a PRECEDES *    |  |
|  |                   |  |
|  |      a   *   #     |  |
|  |                   |  |
|  +-------------------+  |
+-------------------------+
```
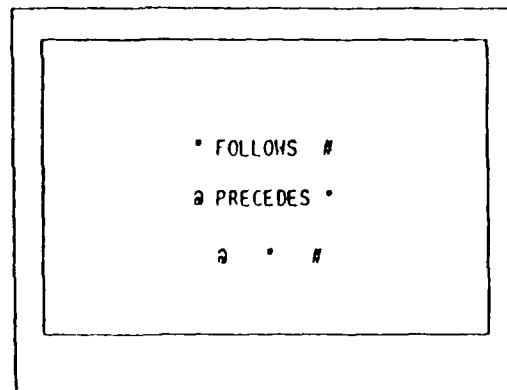
SOLUTION: SENTENCE 1 - FALSE   SENTENCE 2 - TRUE

RESPONSE: FALSE

Figure 3.4.   Grammatical reasoning task video display.

decided to use the resources available to take a broad look at cognitive loading to discover useful areas for future research. Thus it was not possible to train all subjects to asymptotic lev ls of task performance. The impact of this decision is considered in Sections 5.3 and 5.5, where task performance scores are analyzed.

3.5 Experimental Procedure and Data Collection

For each experimental session, subjects were seated in a darkened sound attenuating booth facing a 15 cm x 15 cm window. Behind the window was the stimulus presentation apparatus. For the lights only conditions the subjects were instructed to "relax and fixate on a small square at the center of the display" for the cognitive loading conditions the subjects were instructed to concentrate on the task. Each trial lasted approximately 82 sec. and after every three trials the experimenter entered the booth to inquire about the status of the subject (alertness, fatigue etc). Every sixth trial the subjects were given a 3-6 min break. Sessions were either 12 or 18 trials long. Subjects were advised that the session could be terminated at any time upon their request.

On the average, subjects were exposed to four experi-mental sessions. The first two sessions were used for familiarization and training. Results from the last two sessions, four trials per task condition, were used for data analysis. Data collection for each trial lasted 82 sec,

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resulting in two 40.96 second periods available for data
analysis. This meant there were actually a total of eight
40.96 second trials available for data analysis and
ensemble averaging per condition.

The same PDP 11/60 computer which generated steady-
state and transient stimulus signals was used to collect
experimental data. After passing the EEG signal and the
photocell signal through anti-aliasing filters (General
Radio low pass filters, cutoff set at 30 Hz, 0 dB up to
23 Hz, down 3 db at 30 Hz, 24 dB/Octave rolloff), the two
signals were digitized and stored for subsequent analysis
on a PDP 11/34.

3.6   Data Analysis

3.6.1   Steady State Data Analysis

Given sufficient time for transients to dampen out, a
noise-free linear system driven by a sum-of-sines (SOS)
input will respond only at frequencies contained in the
forcing function. Output effects due to the input,
therefore, are obtained only at input (i.e. SOS)
frequencies. Conversely, system response power obtained
at non-input frequencies is called remnant power, as dis-
cussed in section 3.2.1. Output/Input relationships can be
formulated as transfer functions if the system is purely
linear. For nonlinear systems the linear portion of the
output/input response can be quantified as a describing

function (Kochenburger, 1950), and the nonlinear portion of the output can be described by the remnant power.

The following procedure has often been used to estimate system describing functions and remnant:

1. By means of the DFT, compute Fourier coefficients for the time histories representing the input and output.

2. At each SOS frequency, compute the estimate of the describing function as the (complex) ratio H of the Fourier coefficient of the output signal to the Fourier coefficient of the input signal. Express this estimate in terms of "gain" and "phase shift" (equations 3.3 and 3.4).

$$\text{Gain} = 10 \log (|H|^2)$$
$$\text{Gain in dB} \tag{3.3}$$
$$\text{Phase} = 57.3 \tan^{-1}(\text{Im}\{H\}/\text{Re}\{H\})$$
$$\text{Phase in degrees} \tag{3.4}$$

3. Compute the "spectra" for the input and output signals as the magnitude of the Fourier coefficients.

4. For both the input and output signals, compute the average remnant power in a small frequency band about each SOS frequency. Assume remnant power varies smoothly with frequency, and consider this

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average power to be an estimate of remnant power at the corresponding SOS component frequencies (Junker and Levison, 1980).

5. Compute signal-to-noise (S/N) ratios for both signals dividing the power actually measured at a given SOS frequency by the estimated remnant power at that frequency. If S/N ratios for both input and response are above some criterion level (typically, 6 or 7 dB) at a given SOS frequency, consider the corresponding describing function estimate computed in step 2 to be valid. If the S/N for either the input or the output signal falls below the criterion, conclude that a valid describing function cannot be obtained at that particular frequency.

The above procedure is a reasonable one to follow when considering a single trial, as it prevents the acceptance of a describing function estimate that is likely to be seriously corrupted by output remnant. When performing experiments with human test subjects, however, attempts to improve measurement reliability are generally made by ensemble-averaging the results from a number of replications of a given test condition.

To compute ensemble statistics of a system describing function, the usual procedure is to first compute the describing function (in terms of gain and phase) for each

experimental trial, retaining only those measurements considered valid by the signal-to-noise test. Using only these valid measurements, we then compute the mean and standard deviation of the gain, and mean and standard deviation of the phase shift at each SOS frequency.

While this method is straightfoward, it is deficient in a number of respects. First, it tends to be conservative in that it tests the reliability of each individual measurement rather than of the ensemble mean. As a result, certain measures are unnecessarily discarded. Second, it may yield a frequency response curve that has an inconsistent data base. That is, measurements will be retained from all experimental trials at frequencies where remnant is relatively small, whereas measures from only a subset of trials will generally be retained at frequencies where remnant is significant. Finally, this method tends to overestimate the mean gain, because it retains measurements where remnant power has tended to reinforce the input-correlated portion of the response, and it discards measurements where remnant has tended to counteract the input correlated component.

The ensemble-averaging methodology utilized in this work, except for Sections 4.2 and 5.1, avoids these particular difficulties by using all the available data to compute the ensemble means, and then directly estimating the reliability of the mean. Thus, we retain or reject all the describing function data at a given SOS frequency.

The following procedure was used for estimation of describing functions at each SOS frequency:

1. Compute the describing function complex coefficients and remnant values (Junker and Levison, 1980) for each replicate or trial.

2. Average the describing function measurements (as complex coefficients) across trials.

3. Compute the average remnant variance across trials for each of the SOS frequencies.

4. Compute the estimated gain and phase shift from the average (complex) describing function.

5. Estimate the standard errors of the gain and phase estimates at each SOS frequency using the following equations:

$$SE_{GAIN} = 6.14 \left[\frac{1}{N-1} \left(\frac{\overline{|H|^2}}{|\overline{H}|^2} - 1 \right) \right]^{\frac{1}{2}} \quad (3.6)$$

$$SE_{PHASE} = 6.60 \; SE_{GAIN} \quad (3.7)$$

H = Describing function complex coefficients
N = Number of trials

For a detailed discussion and explanation of the development of the above equations the interested reader is referred to Levison (1985).

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3.6.2 Transient Data Analysis

For analysis of transient stimulation data, time lock averaging of each of the 40 segments for each trial for each of the two signals was done first. Then averaging across trials for each condition (4 trials per condition) was performed. Time responses were plotted to allow visual comparisons across lights only and task loading conditions. In addition, time responses were Discrete Fourier Transformed and describing function gain and phase values were computed. The describing functions were plotted, for visual comparison, with sum-of-sines generated describing functions. This is graphically illustrated in Figure 3.5.

3.6.3 Phase Unwrapping

The Fourier analysis scheme embedded within the frequency response analysis program yields somewhat ambiguous phase-shift estimates. Because phase repeats every 360 degrees, we can shift estimates by an integral multiple of plus or minus 360 degrees and not violate the frequency response analysis. In general, the frequency analysis scheme must be accompanied by a procedure for "umwrapping" the phase in a meaningful way. Otherwise, frequency shaping of the phase response will have a sawtooth appearance, since Fourier analysis schemes can
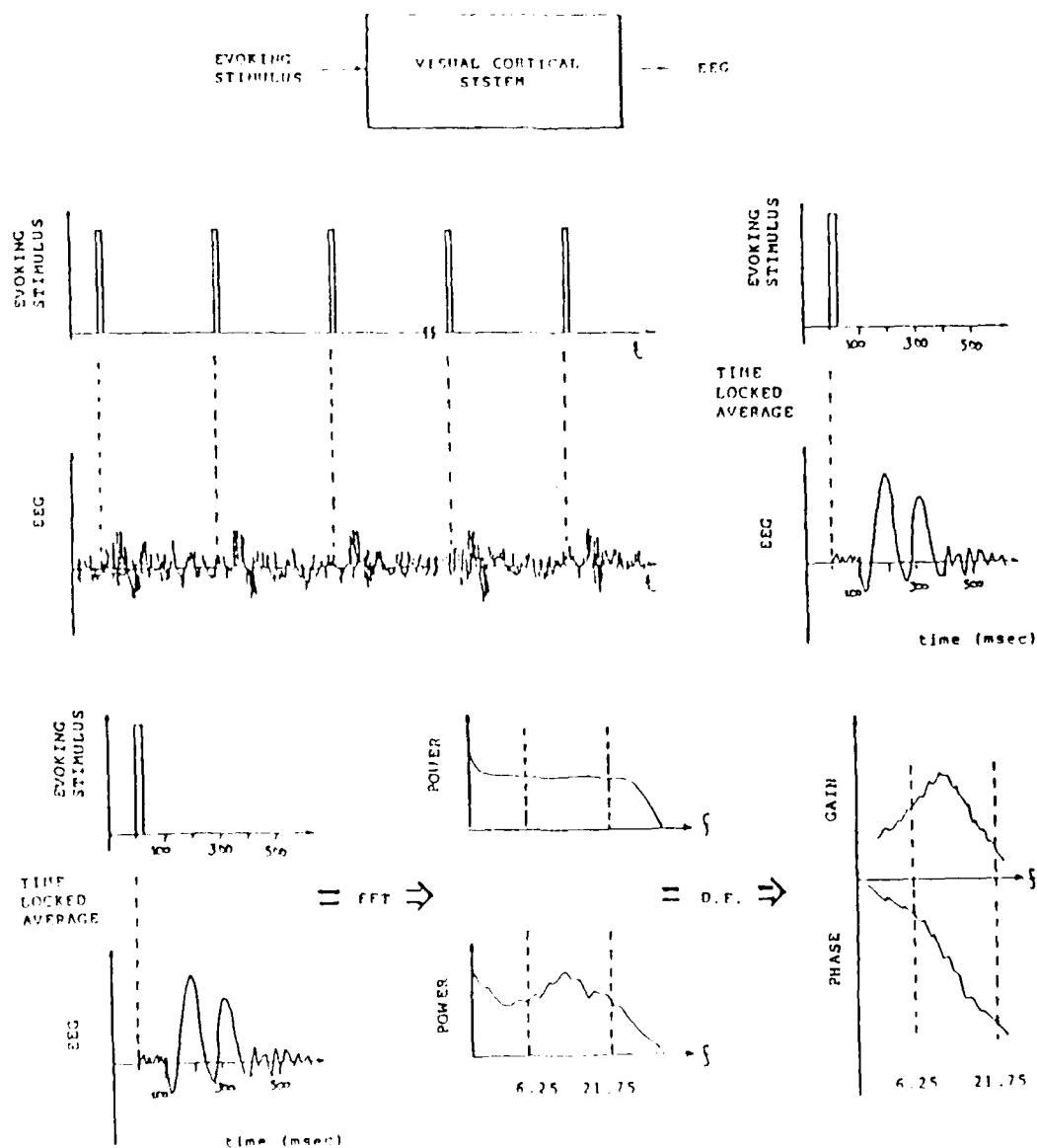
Figure 3.5. Transient data analysis procedure.

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only identify phase shift within a single cycle (typically, 0 to 360, or -180 to 180 degrees). A representative second order describing function has been plotted in Figure 3.6 to illustrate this phenomenon. Two methods were employed to unwrap the phase values; a graphical approach, and model analysis and phase unwrapping combined into one operation.

The graphical approach consisted of plotting the average phase values as illustrated in Figure 3.6a and identifying the points where wrapping occurred. The Fourier analysis scheme produced phase values between -180 and 180 degrees. Values close to these extremes indicated points of phase wrapping. Phase values beyond these points were simply shifted -360 degrees, or one cycle. Each succeeding phase value was shifted a number of cycles corresponding to the number of points of phase wrapping preceding it. The technique was easy to implement and the points where the phase curve needed to be unwrapped were usually clearly identifiable. Points on the phase curves where it was not always clear whether to unwrap or not often corresponded to areas of peaking of the gain curve. This is reasonable to expect, as a highly resonant system may well exhibit large changes in phase-shift in the region of resonance. For the majority of data presented in this report the graphical approach was employed.

The second approach was part of the modeling effort of Section 6.2. Certain assumptions had to be made in

Fig 3.6a
Phase Wrapped
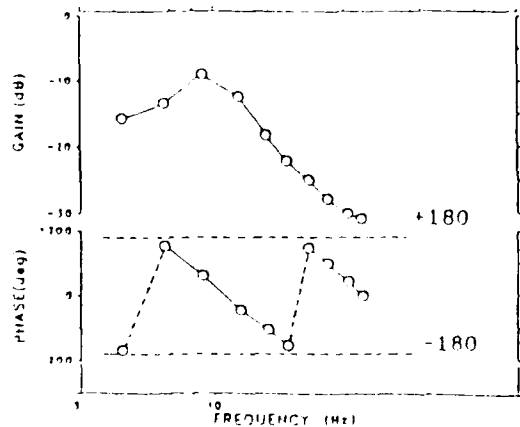
Fig 3.6b
Phase Unwrapped
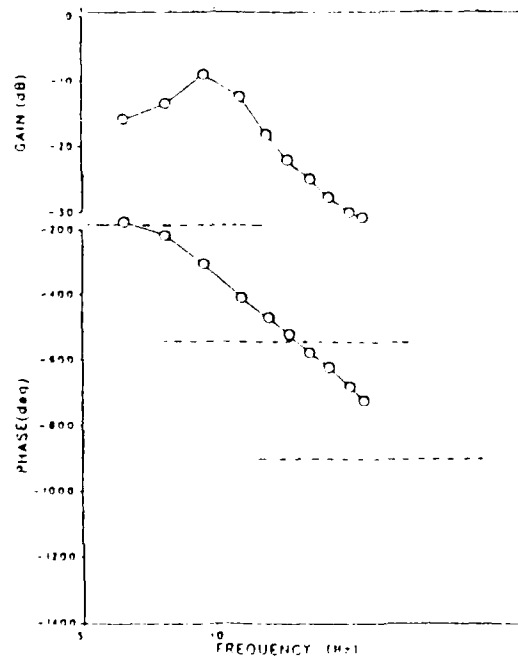
Figure 3.6.   Response of a representative second order
system (gain = 0.1, time delay = .07 sec,
resonant frequency = 10 Hz and, damping
coefficient = .15).   Figure 3.6a illustrates
how Fourier transformation provided wrapped
phase data.   Figure 3.6b illustrates how it
can be unwrapped by graphically adding -360
degrees, for each wrapping of the phase
curve, to the phase values.

order to derive a method which incorporated modeling for unwrapping the phase. In the case of manual control data, it is usually assumed that phase varies relatively smoothly with frequency. That is, it is assumed that the frequencies at which frequency response estimates are obtained are sufficiently close together so that successive phase estimates are unlikely to differ by more than 180 degrees. The phase is simply unwrapped by adjusting the phase at each measurement frequency by the number of cycles required so that it does not differ from the preceding (in frequency) estimate by more than 180 degrees. A reference point is also assumed for the phase obtained at the lowest measurement frequency, usually 0 or -180 degrees.

As mentioned above, the assumption of a smoothly varying phase response is not always justified with the visually evoked EEG data. A highly resonant system may well exhibit sharp changes in phase-shift in the region of the resonance.

To avoid the constraint that successive phase measurements differed by less than 180 degrees, it was assumed that the phase and gain curves were related to each other in an orderly manner, and that it could be described analytically (typically, a linear model). In this way, the experimental phase shift was unwrapped with respect to a model generated baseline. This is perhaps one of the few instances in which it was legitimate to

"adjust the data to fit the model" as the adjustments were integral multiples of 360.

In general, the use of a model to unwrap the phase curve implies a model matching exercise. A single iterative procedure was employed to select jointly parameters which best characterized the data and unwrapped the phase. Ideally, the model used for this purpose is a "theoretical model"; i.e., one that is expected on theoretical grounds to provide a good match to the data. At present, theoretical models of the type available for manual control do not exist for the SSEP. Unlike the manual control task, where a specific response strategy can usually be derived for accomplishing well-defined control objectives (particularly in a laboratory setting), the SSEP is not known to have a similar teleological foundation. Unless one is using the SSEP for biofeedback in a control loop, it is not clear why the electrocortical potentials recorded from the scalp should bear any particular relationship to the visual stimulus. This issue will be addressed further in Section 7.5. Thus, to the extent that this technique relied on model analysis to unwrap the SSEP phase data, descriptive models had to be used. The following scheme was developed and applied:

1. Select an analytic model form of the lowest order that seemed likely to provide an acceptable match to the data.

2. Select an initial set of model parameters, based on certain features of the frequency response

3. Using the current model parameters, predict gain and phase at each measurement frequency.

4. Readjust the experimental phase shift at each frequency, where necessary, by an integral multiple of 360 degrees until the experimental phase estimate is within 180 degrees of the corresponding model prediction.

5. Using an appropriate adjustment scheme, readjust independent model parameters to improve the match to the data.

6. Iterate on steps 3-5 until the matching criteria are satisfied.

The details of using this scheme to unwrap phase data and model results are presented in Section 6.2.

4. CHARACTERISTICS OF THE EEG MEASURES

Characteristics of the EEG measures are presented in this section. The specificity of the evoked response, presented in terms of EEG power spectra, is considered in Section 4.1. The results of investigating stimulus parameter effects on the visual-cortical response are presented in Section 4.2. Visual-cortical response measurements have been made for a number of years, providing indications of the repeatability of the measure over time. This repeatability in terms of visual-cortical describing functions, over a three year span, is described for two subjects in Section 4.3. In Section 4.4, results from a study in which comparisons were made between steady-state and transient evoked potentials are presented.

4.1 Specificity of Response

One of the first concerns to be addressed during this project was whether or not an identifiable response to a sum-of-sines stimulus could be found in the electro-cortical recordings. Early data collection and analysis was done with a Nicolet Fourier analyzer. Results are shown for two subjects in Figures 4.1 amd 4.2. Shown in both figures are power spectra for the visual stimulus and
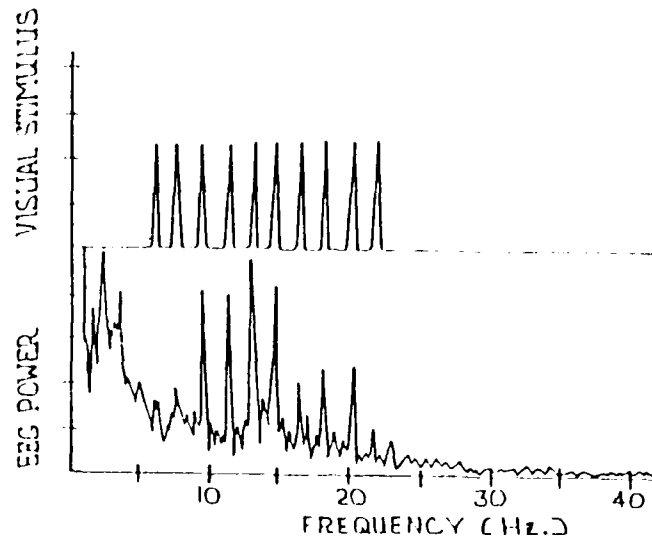
Figure 4.1. Power spectra of visual stimulus and EEG, illustrating the relationship between the two signals. EEG peaks indicate visual-cortical responses due to the evoking stimulus. Data is from Subject 02.
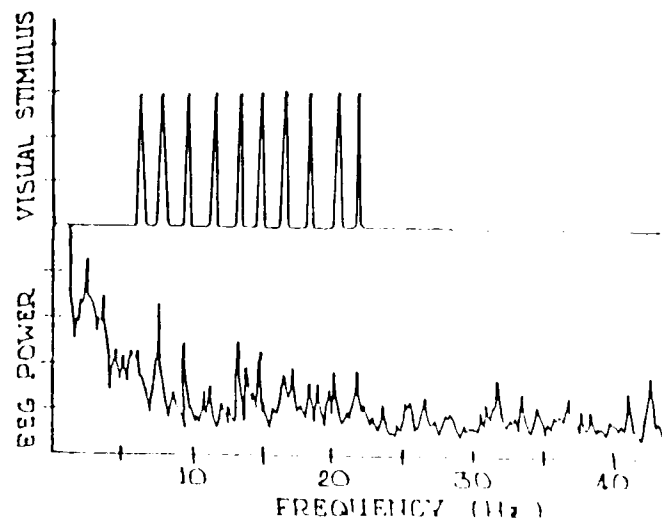
Figure 4.2. Power spectra of visual stimulus and EEG, for Subject 01.

the EEG of the subjects. From these plots it can be seen that subjects respond to the stimulus frequencies, some frequencies stronger than others.

From analysis of this data, problems with the stimulus/analysis system became apparent. The input power peaks spanned a wide frequency band (perhaps 1 or 2 Hz) indicating smearing of the input power. Due to the lack of analysis sensitivity of the Nicolet system, this smearing of power could not be explained. Of equal concern was the observed smearing in the EEG spectra. These results left the question of the specificity of the SOS driven EEG response unclear.

To overcome these problems the computer that generated the SOS inputs (a PDP 11/60) was also used to collect the responses. This provided a guaranteed synchrony and an improved resolution of 0.0244 Hz.

The effectiveness of this data collection system and, likewise, the preciseness of the evoking stimuli and specificity of the EEG signals can be observed in expanded views of their power spectrums. Results are presented for one subject (Subject 05) in Figures 4.3 and 4.4. Expanded spectral plots are plotted for two of the sum-of-sines frequencies. Figure 4.3 shows the power of the spectral responses about the eighth frequency (18.25 Hz) and Figure 4.4 is a plot of the spectral power about the third frequency (9.49 Hz). In each figure power spectral values are depicted for: the evoking stimulus, the evoked
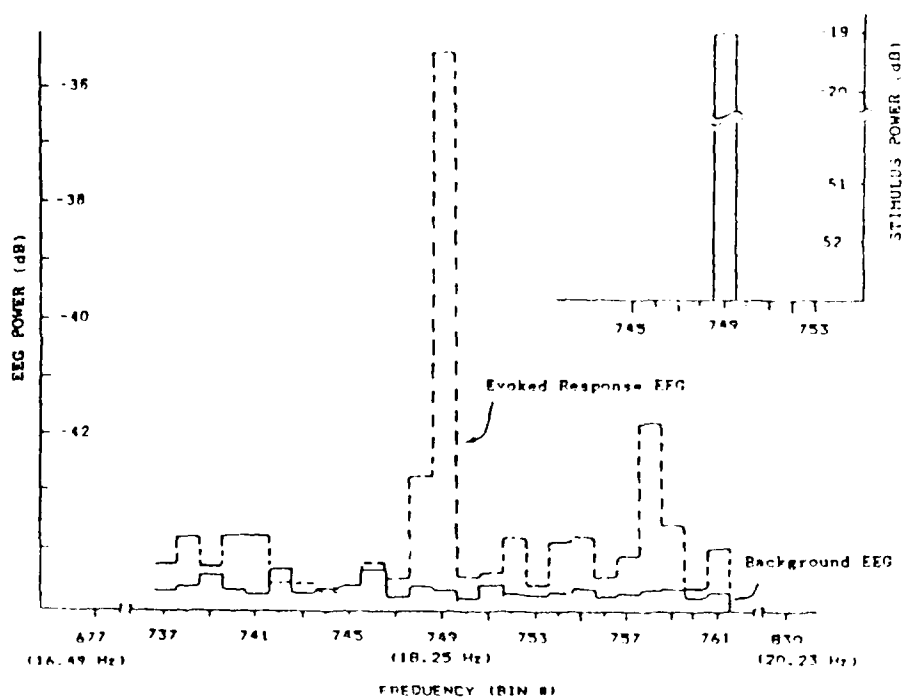
Figure 4.3. Specificity of the evoked response centered about 18.25 Hz (beta band), for Subject 05.
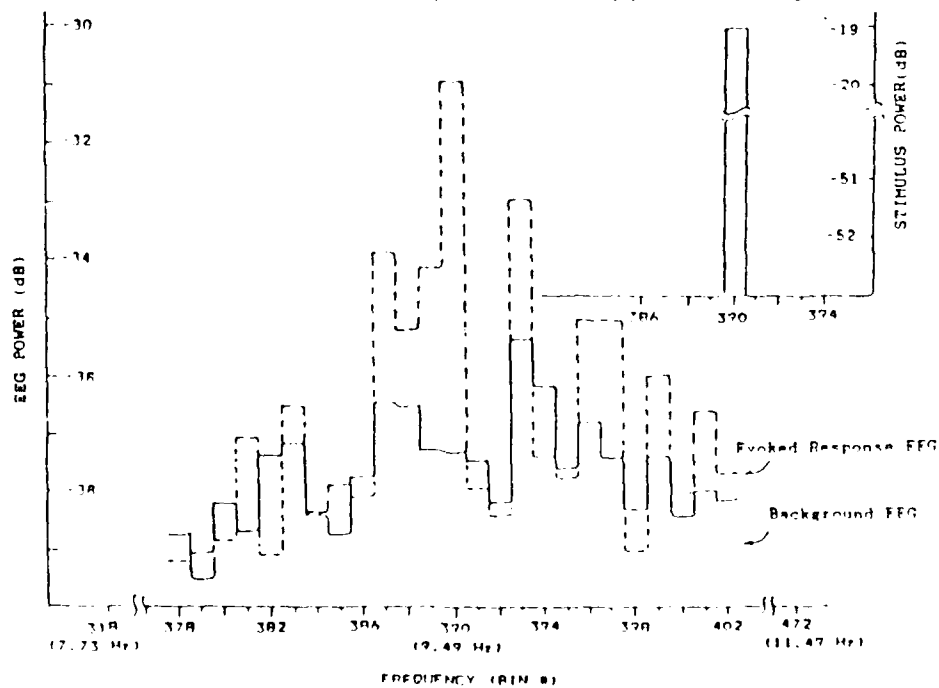
Figure 4.4. Specificity of the evoked response centered about 9.49 Hz (alpha band), Subject 05.

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response EEG, and the EEG with no evoking stimulus present. The EEG, with no evoking stimulus, is referred to as background power.

The upper right hand graph of Figure 4.3 indicates the frequency narrowness, and thus frequency purity, of the stimulus power. This was power as measured by the photocell (Figure 3.1). The power (-19 dB) appears in only one frequency band, or bin. Adjacent power is minimal (below -53 dB). As mentioned in Section 3.2.1, with the PDP 11/60 and 11/34 computers, a frequency resolution of 0.0244 Hz was achieved. This is a measure of the smallest frequency band resolvable with the system. Within a frequency bin any measurement represents the average power for that bin. Thus Figures 4.3 and 4.4 are presented as bar graph plots of power versus frequency bin number. The frequency associated with a particular bin is equal to the bin number minus 1 times the bandwidth (.0244 Hz). The bin number minus 1 is also equal to the harmonic the fundamental.

The specificity of the evoked EEG response to the 25 Hz sine wave when compared to background EEG power levels was obvious (Figure 4.3). The evoked response appeared predominantly in the corresponding input frequency bin. To insure that the evoked response was not stimulus contamination of the EEG, similar measurements were obtained with the subject blindfolded. As expected, there was no response to the stimulus.

Figure 4.4 shows the effects of the evoking stimulus at 9.49 Hz. This is within the alpha region of the EEG spectrum. This subject consistently exhibited greatest power within this region. Because this subject was a large "alpha producer" (greatest evoked response and background EEG levels in the alpha region) it was of interest to determine what the specificity of the evoked response would be to a sine wave stimulus in this region. The evoked response to the stimulus was significant, however there was a marked increase in the background EEG power as well. These results suggest that the evoked response and background EEG power may be more coupled together in this frequency region than in the mid-frequency region (14 to 20 Hz). This is suggested for this subject who exhibits large alpha power. For subjects with other than alpha resonance properties, the coupling may be expected to occur at the frequency of resonance.

The results as shown in Figures 4.3 and 4.4 were used to help confirm the selection of the width of the remnant computation window. It was chosen to span 10 frequency bins below and 10 frequency bins above each evoking stimulus frequency. This resulted in a frequency range of 0.512 Hz over which average EEG power (excluding the center frequency bin of stimulation) or remnant power was computed. From these results, it was felt that the remnant window was wide enough to capture the background effects relative to the evoked response and at the same time

narrow enough to avoid any evoked responses from harmonics
or first-order nonlinear effects.

Section 4.2 Stimulus Parameter Effects

A sinusoidally modulated light can be characterized
by: frequency, phase, average intensity, and depth of
modulation. Likewise SOS light input can be characterized
by these four parameters. In Section 3.2.1 the method
used to select frequency and phase for the SOS input was
described. Selection of these two parameters was based
upon a need to stimulate the visual-cortical system with a
minimum of nonlinear side effects.

To better understand how to specify the other two
parameter values and to investigate the effects of these
parameters on the visually evoked potential, a study was
performed in which two different intensity levels and two
different depths of modulation were used. The intention
of this study was to determine the best values for
modulation and intensity of the evoking stimulus for
subsequent investigations. The results of this study are
presented in this section.

The two average intensity levels used were 40 ft-L
and 80 ft-L as determined by a Minolta Luminance meter at
the subject's viewing location (Figure 3.1). Both average
intensity levels were subjectively determined to be low
enough to comfortably allow simultaneous viewing of video

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displayed computer controlled tasks. The higher average intensity was close to an upper limit of subjective acceptability however.

Previous studies (Spekreijse, 1966, Regan and Beverley, 1973, Wilson, 1980, and Wilson and O'Donnell, 1980) indicated that evoked potential responses increased with increasing strength of the evoking stimulus. Stimulus strength can be changed in two ways; by changing the average intensity, and by changing the depth of modulation. As discussed in Section 3.2.1, the maximum depth of modulation possible for each of 10 sine waves of an SOS signal is 14.7% to keep the SOS signal less than 100% modulated 99.1% of the time (3 sigma) With this upper limit in mind, two levels of depth of modulation were selected to be tested: 13% and 6.5%.

An experiment was run using 10 subjects (4 males and females, 20 to 40 years in age). Each subject was exposed to 4 experimental sessions. Each session consisted of 2 exposures to each of the 4 conditions presented in a random fashion.

EEG data was collected and analyzed using the digital computer methodology described in Section 3.6.1. To determine the effectiveness of the stimulus parameter values, three EEG measures were selected for analysis as dependent variables. The first was CORrelated EEG Power (CORP). CORP, obtained from the "spectra" of the EEG signal, was the power actually measured at each of the 10

SOS frequencies. The second dependent variable considered was REMnant power (REM), the average power in a band about each of the given SOS frequencies, excluding the power actually measured at the SOS frequencies (refer to Sections 3.2.1 and 3.6.1). The third dependent variable considered was describing function GAIN (GAIN), computed using equation 3.3. The first two dependent variables, CORP and REM, were chosen because they represent direct measures of EEG output. Describing function measures on the other hand, are complex ratios of system output divided by stimulus input. For a linear system, a change in input would cause a corresponding output change, as the gain of a linear system is independent of the input. GAIN was chosen as the third dependent variable to provide insights into the linearity of the visual-cortical system in relation to the stimulus parameter values.

Each Subject (Ss) was exposed to a total of 4 runs, 2 per day, for each stimulus condition. Data from the last two sessions for each subject were used for analysis. Each run consisted of two 40.96 sec stimulus periods back to back (Section 3.5). Data presented here represent the average of eight 40.96 sec exposures at each stimulus SOS frequency for each condition. The first steps in the analysis were computation of spectra and computation of values for the three dependent variables at each SOS frequency. Using a statistical analysis package, the next step was to collapse or average data across all eight

runs for each subject per condition. Separate analyses
were then performed for each of the dependent variables.

4.2.1 Effects on CORP

For the initial analyses, data was reduced further by
averaging across subjects. This was done as a means of
eliminating the effects due to individual differences,
thereby providing a clearer picture of the general effect
of the various independent variables. A 3-way ANalysis Of
VAriance (ANOVA) was performed on the data with the major
factors being; the two depths of MODulation (MOD), the two
INTensities (INT), and the 10 stimulus FREQuencies (FREQ).
Table 4.1 is the resultant ANOVA summary table for this
analysis.

Figure 4.5 is a plot of CORP vs MOD (collapsed across
FREQ) for both high and low levels of intensity. Compar-
ing Figure 4.5 with Table 4.1 reveals that the significant
main effect of MOD ($p < .01$) is a result of a stronger
CORP response with increasing values of modulation. INT
exhibits a trend in the expected direction of an increased
CORP response as intensity increases. This trend was not
statistically significant ($p > .1$) however, due to the
significant interaction ($p < .05$) between MOD and INT.
That is, at the low level of MOD, increasing INT resulted
in a stronger CORP response. However, at the higher level
of MOD, increasing INT resulted in no change in CORP. It
is hypothesized that this interaction is a consequence of

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TABLE 4.1 ANOVA summary, effects on CORP

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
MOD	1	87.8926	29.48	0.0004
INT	1	9.7637	3.27	0.1038
FREQ	9	680.1858	25.35	0.0001
MOD*INT	1	17.4485	5.85	0.0367
MOD*FREQ	9	32.8109	1.22	0.384?
INT*FREQ	9	33.9310	1.26	0.3662

TABLE 4.2 ANOVA summary, effects on CORP, with Ss

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
Ss	9	12619.1001	48.19	0.0001
MOD	1	878.9260	30.21	0.0001
INT	1	97.6378	3.36	0.0681
FREQ	9	6801.8583	25.97	0.0001
Ss*MOD	9	503.4194	1.92	0.0489
Ss*INT	9	408.6194	1.56	0.1267
Ss*FREQ	81	13889.7222	5.89	0.0001
MOD*INT	1	174.4859	6.00	0.0150
MOD*FREQ	9	328.1097	1.25	0.2626
INT*FREQ	9	339.3101	1.30	0.2386

TABLE 4.3 Effects of MOD on CORP, by Subject

| Subj # | CORP (dB) | | Effect of Mod |
	(6.5% Mod)	(13% Mod)	Increase
01	-33.22	-35.07	-1.85
02	-42.96	-40.52	+2.44
03	-41.43	-39.02	+2.41
05	-33.78	-32.07	+1.71
07	-45.87	-42.98	+2.89
08	-53.05	-47.04	+6.01
09	-49.79	-43.00	+6.79
10	-39.10	-35.09	+4.01
14	-34.19	-31.51	+2.68
15	-44.14	-41.53	+2.61
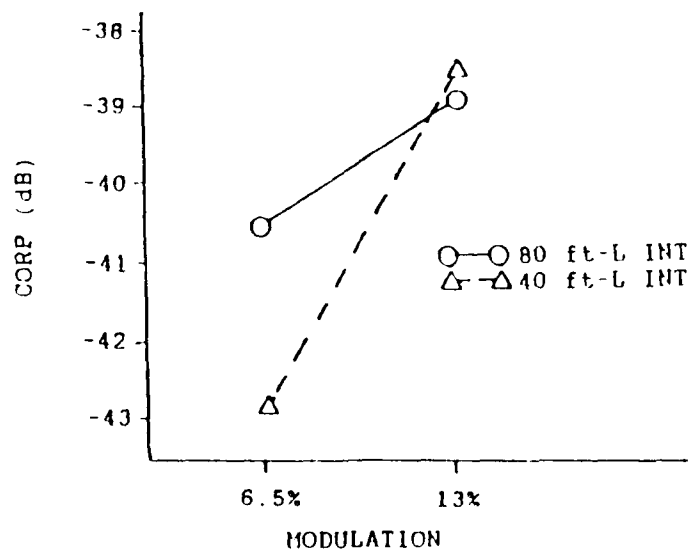
Figure 4.5. CORrelated EEG Power vs stimulus depth of MODulation, two levels of stimulus INTensity, collapsed across subjects and frequencies.
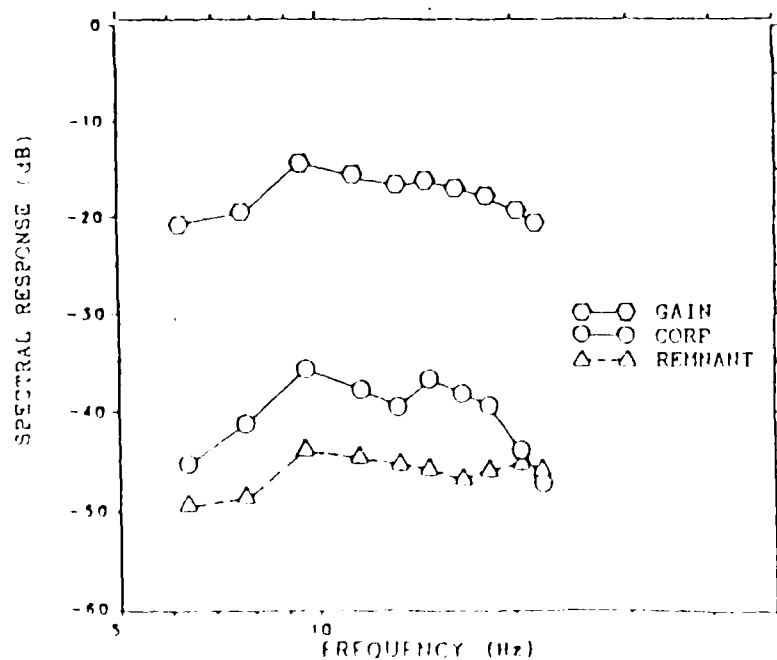
Figure 4.6. Describing function GAIN, CORrelated Power, and REMNANT, vs frequency. Collapsed across subjects, modulation and intensity.

saturation of the visual-cortical response. That is, the condition of high MOD and low INT is such that it produces the maximal EEG response. Thus a further increase in INT results in no change in the EEG response.

Finally, Figure 4.6 is a plot of CORP vs FREQ collapsed across both MOD and INT. This plot illustrates that the significant main effect of FREQ ($p < .01$) is a consequence of the bandpass characteristics of the visual-cortical response system. That is, the system produces a relatively strong response to frequencies in the range of 9.49 Hz to 18.25 Hz but a much weaker response to frequencies higher or lower than these. No other significant effects were observed.

To assess the effects of individual differences, a second analysis was conducted, without averaging across subjects. This was a 4-way ANOVA with the major factors being: Subjects (Ss), MOD, INT and FREQ. Table 4.2 is the resultant ANOVA summary table.

A review of Table 4.2 reveals that both Ss and MOD exhibited significant main effects ($p < .01$), while the main effect of INT was insignificant ($p > .05$). However, the 2-way interaction with Ss and MOD was also significan' ($p < .05$). These results indicate that individual Ss differences are somewhat important. A review of the raw data revealed that as MOD increased, 9 of the 10 Ss exhibited a corresponding increase in CORP (Table 4.3).

Also noteworthy in Table 4.2 is the significant main

effect of FREQ (p < .01) as well as its significant
interaction with Ss. Here again, a review of the raw data
revealed that the main effect was due to the bandpass
characteristics of the visual-cortical response system.
The significant interaction is a consequence of different
subjects having different frequency responses. In
general, however, all subjects exhibited stronger
responses to the middle frequencies. Finally, the
significant interaction of MOD and INT (previously
attributed to saturation effects) was still observed. No
other significant effects were observed.

4.2.2 Effects on Remnant

As was done previously, the first step in the
statistical analysis was to average the data across
subjects. Next, a 3-way ANOVA (major factors being: MOD,
INT and FREQ) was conducted. The results are summarized
in Table 4.4.

The main effect of MOD was found to be insignificant
(p > .1). This is an important finding in that it means
MOD can be increased to produce a stronger evoked response
(based on the previous findings for CORP), without a
concurrent increase in REM. The main effect of INT was
found to be significant (p < .05). Table 4.5 is a list of
REM vs INT. It can be seen that the effect of INT is a
consequence of higher INT producing an increased REM.
This finding is consistent with the previously noted

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TABLE 4.4   ANOVA summary table, effects on REM

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
MOD	1	0.1095	2.85	0.1255
INT	1	0.3045	7.93	0.0202
FREQ	9	115.0626	332.97	0.0001
MOD*INT	1	0.3637	9.47	0.0132
MOD*FREQ	9	0.2989	0.87	0.5837
INT*FREQ	9	0.5972	1.73	0.2136

TABLE 4.5   Effects of INT on REM

REM (dB)		Effect of INT
@ 40 ft-L	@ 80 ft-L	Increase
-46.71	-46.53	+0.18

TABLE 4.6   ANOVA summary, effects on REM, with Ss

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
Ss	9	3242.0418	539.84	0.0001
MOD	1	1.0955	1.64	0.2012
INT	1	3.0465	4.57	0.0336
FREQ	9	1150.6268	191.59	0.0001
Ss*MOD	9	78.6303	13.09	0.0001
Ss*INT	9	52.6909	8.77	0.0001
Ss*FREQ	81	1943.4613	36.05	0.0001
MOD*INT	1	3.6378	5.45	0.0205
MOD*FREQ	9	2.9696	0.50	0.8760
INT*FREQ	9	5.9721	0.99	0.4453
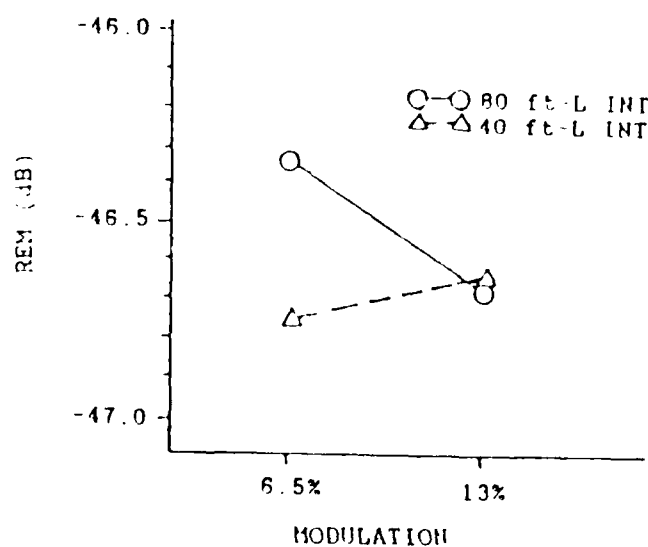
Figure 4.7. REMnant power vs stimulus depth of
MODulation, two INTensity levels. Collapsed
across subjects and frequencies.

Figure 4.8. Effects of stimulus parameters; MODulation,
and INTensity, on visual-cortical evoked
CORrelated Power.
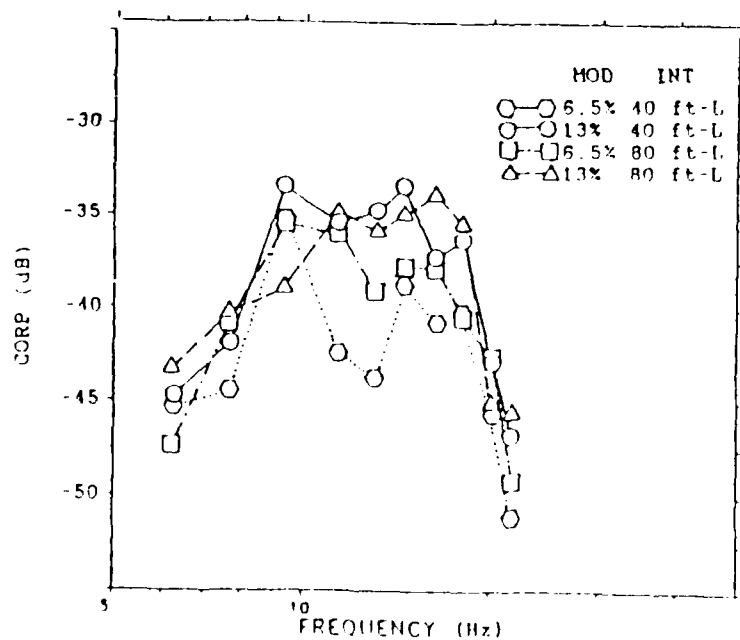
hypothesis that the higher level of INT drove the visual-cortical system into saturation.

The main effect of FREQ was also found to be significant (p < .01). A review of the raw data did not reveal any specific trends, rather the effect was due to differential remnant across the frequency range (see Figure 4.6). The trend in the remnant data of Figure 4.6 can be attributed to alpha peaking for some subjects.

Finally, the interaction between MOD and INT was again observed to be significant (p < .05). Figure 4.7 is a plot of REM vs MOD for both levels of INT. At 40 ft-L, an increase in MOD had only a minor effect on REM. At 80 ft-L however, an increase in MOD resulted in a decrease in REM. It can be seen that the nature of this effect is the same as was previously observed for CORP (note Figure 4.5). No other significant effects were observed.

To assess the effects of individual differences, a second analysis was conducted without averaging across subjects. Thus a 4-way ANOVA (major factors being: Ss, MOD, INT, and FREQ) was conducted. The results are summarized in Table 4.6.

As was the case with CORP, these results were consistent with the previous findings. The main effects of Ss was highly significant (p < .01) indicating the importance of individual differences. The main effect of MOD was not significant (p > .10), and the main effect of INT was significant (p < .05). FREQ was also significant

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(p < .01), but again due to the trend noted above (refer
to Figure 4.6). All three 2-way interactions between Ss
and MOD, INT. and FREQ were significant (p < .01).
However, a review of the raw data revealed that all three
interactions were a consequence of inconsistencies in the
direction of the effects (i.e. as MOD was increased some
Ss exhibited an increase in REM while others showed a
decrease). Again, these findings clearly demonstrate the
importance of considering individual differences. No
other significant findings were observed.

4.2.3 Effects on Gain

As before, the first step in the statistical analysis
was to average the data across Ss. Then a 3-way ANOVA
with the factors of MOD, INT, and FREQ was conducted. The
results are summarized in Table 4.7.

The main effect of all 3 factors was found to be
significant (p < .01). Table 4.8 lists the effects of MOD
and INT on GAIN. It indicates that the effect of an
increase in MOD (doubling the modulation, a 6 dB increase)
caused a decrease in GAIN. System gain is proportional to
the magnitude of the system output divided by the
magnitude of the system input. If the system input is
increased by 6 dB and the system output only increases by
2 dB, the gain will appear to decrease by 4 dB. A linear
model would predict no change. It is hypothesized that
the GAIN showed a decrease because the magnitude of the

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TABLE 4.7   ANOVA summary table, effects on GAIN

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
MOD	1	227.9543	572.29	0.0001
INT	1	228.2432	573.02	0.0001
FREQ	9	212.3403	59.23	0.0001
MOD*INT	1	0.6933	1.74	0.2190
MOD*FREQ	9	15.2046	4.24	0.0213
INT*FREQ	9	5.8154	1.48	0.2836

TABLE 4.8   Effects of MOD on GAIN

GAIN (dB)		Effect of MOD
@ 6.5%	@ 13%	Increase
-15.39	-20.16	-4.74

TABLE 4.9   Effects of INT on GAIN

GAIN (dB)		Effects of INT
@ 40 ft-L	@ 80 ft-L	Increase
-15.39	-20.16	-4.77

TABLE 4.10   Effects MOD on GAIN, across FREQ

FREQ (Hz)	GAIN (dB) (6.5% MOD)	(13% MOD)	Effect of MOD increase
6.25	-18.43	-24.02	-5.59
7.73	-16.75	-23.02	-6.27
9.49	-10.77	-17.66	-7.11
11.49	-14.10	-17.00	-2.90
13.25	-14.96	-18.07	-3.11
14.74	-13.97	-18.04	-4.07
16.49	-14.48	-18.72	-4.24
18.25	-15.34	-19.59	-4.25
20.23	-16.50	-21.90	-5.40
21.74	-18.56	-23.59	-5.03

change of the EEG response could not keep pace with the change of MOD. The relationship of GAIN vs INT in Table 4.9 is a consequence of the same basic phenomenon.

Figure 4.6 includes a plot of GAIN vs FREQ which illustrates that the effect of FREQ is again due to the bandpass characteristics of the visual-cortical system.

The interaction between MOD and FREQ was found to be significant ($p < .05$). Table 4.10 illustrates that this interaction is a consequence of differences in the magnitude of the effect of MOD at different frequencies. It should be noted that the direction of the effect is consistent across all frequencies. Thus the main effect of MOD is reliable. No other effects were observed.

To assess the effects of individual differences, the ANOVA were redone with the added factor of subjects. The results are summarized in Table 4.11.

Again the main effects of all 4 factors were significant ($p < .01$) as were all 3 interactions between Ss and MOD, INT, and FREQ. Table 4.12, GAIN vs MOD for each Ss, clearly demonstrates that the interaction was a consequence of the magnitude of the effect of MOD on each subject, but not the direction. Thus the main effect of increased MOD causing a reduced GAIN is reliable and consistent. Similarly, Table 4.13 lists GAIN vs INT for each Ss. Again the conclusions are basically the same in that 9 of the 10 Ss showed a consistent response while one S exhibited only a slight response in the opposite

TABLE 4.11   ANOVA summary, effects on GAIN, with Ss

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
Ss	9	4359.4883	94.60	0.0001
MOD	1	2279.5432	445.18	0.0001
INT	1	2282.4327	445.75	0.0001
FREQ	9	2123.4033	46.08	0.0001
Ss*MOD	9	718.3610	15.59	0.0001
Ss*INT	9	432.7376	9.39	0.0001
Ss*FREQ	81	3527.4244	8.50	0.0001
MOD*INT	1	6.9330	1.35	0.2458
MOD*FREQ	9	152.0465	3.30	0.0008
INT*FREQ	9	53.1547	1.15	0.3253

TABLE 4.12   Effect of MOD on GAIN, by Subject

	GAIN (dB)		Change with MOD
Subj #	(6.5% MOD)	(13% MOD)	increase
01	-10.55	-22.65	-12.10
02	-14.25	-19.67	-5.42
03	-15.21	-19.62	-4.41
05	-10.45	-15.48	-5.03
07	-19.00	-23.58	-4.58
08	-20.06	-22.87	-2.81
09	-21.00	-22.61	-1.61
10	-14.87	-17.82	-2.15
14	-9.93	-14.49	-4.56
15	-18.54	-22.82	-4.28

TABLE 4.13   Effect of INT on GAIN, by Subject

	GAIN (dB)		Change with INT
Subj #	(40 ft-L)	(80 ft-L)	increase
01	-16.82	-16.38	+0.44
02	-15.38	-18.53	-3.15
03	-13.60	-21.23	-7.63
05	-10.09	-15.84	-5.75
07	-18.96	-23.62	-4.66
08	-18.41	-24.52	-6.11
09	-18.81	-24.80	-5.99
10	-14.14	-18.55	-4.31
14	-9.37	-15.05	-5.68
15	-18.25	-23.11	-4.86

direction. Thus the main effect of INT was consistent across Ss but not as strong as the effect for MOD. This too is consistent with the findings for CORP. An inspection of the raw data revealed that interaction between Ss and FREQ was not due to any consistent pattern, but rather a consequence of different frequency responses across Ss.

In considering these results, it is important to keep in mind that GAIN is proportional to the ratio of CORP divided by stimulus power which is a function of MOD and INT. Doubling either MOD or INT results in a 6 dB stimulus increase. If the visual-cortical response were to keep pace with this increase, GAIN would show little or no change. Referring to Tables 4.12 and 4.13, this was not the case. For some subjects the overall change was close to 6 dB, suggesting that there was no change in the evoked response. For most subjects, the change was less than 6 dB, indicating that there was an increase in the evoked response related to the increase in stimulus power. The important finding here is that GAIN is not a good dependent variable to use for evaluation of the effects of stimulus parameter changes. As mentioned above, it is hypothesized that the relationship of GAIN to MOD and INT is a result of saturation of the visual- cortical system.

4.2.4 Summary of Effects

The following important findings were observed: 1). The higher MOD and lower INT produced the maximum evoked

response. 2). Increasing MOD affected CORP and not REM. 3). GAIN was not a good dependent variable for evaluating stimulus parameter effects since it is related to the ratio of CORP to MOD and INT. and 4). Individual differences were important, indicating that a different approach such as graphical analysis or modeling would be a more effective way to assess system changes.

CORP vs FREQ values are plotted in Figure 4.8 for the 4 stimulus conditions (2 MOD and 2 INT). This shows clearly the saturation effects that occurred in the alpha band. As noted above, the 13% and 40 ft-L conditions produced the "best" response. Increasing INT resulted in further saturation. As a result of these findings, stimulus parameter values of 13% and 40 ft-L were selected for the remainder of the work for this report, with the exception of Section 5.1, which was an extension of this particular effort.

Remnant values for the 4 stimulus parameter conditions are plotted in Figure 4.9. Only slight differences across conditions can be seen. These small differnces, plus the statistical results of Table 4.4 indicate that remnant is only mildly affected by a visual evoking stimulus, while the evoked response is strongly affected by characteristics of visual stimulus (Figure 4.8).
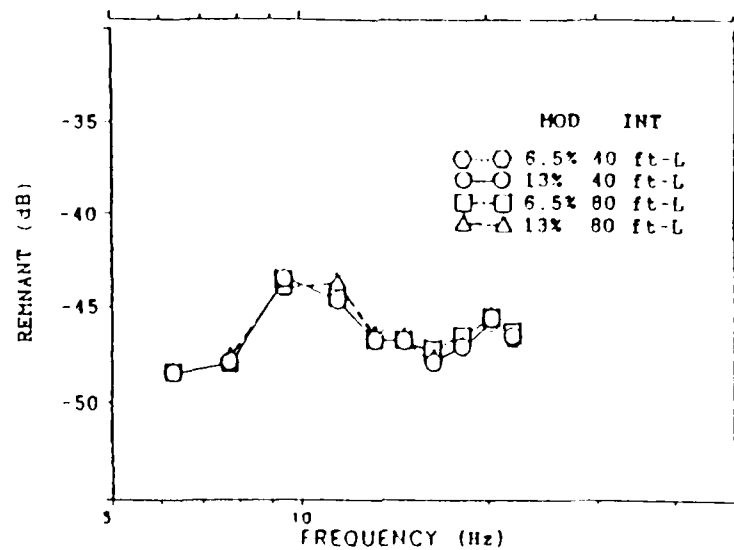
Figure 4.9.   Effects of stimulus parameters; MODulation, and INTensity, on background EEG or REMNANT.
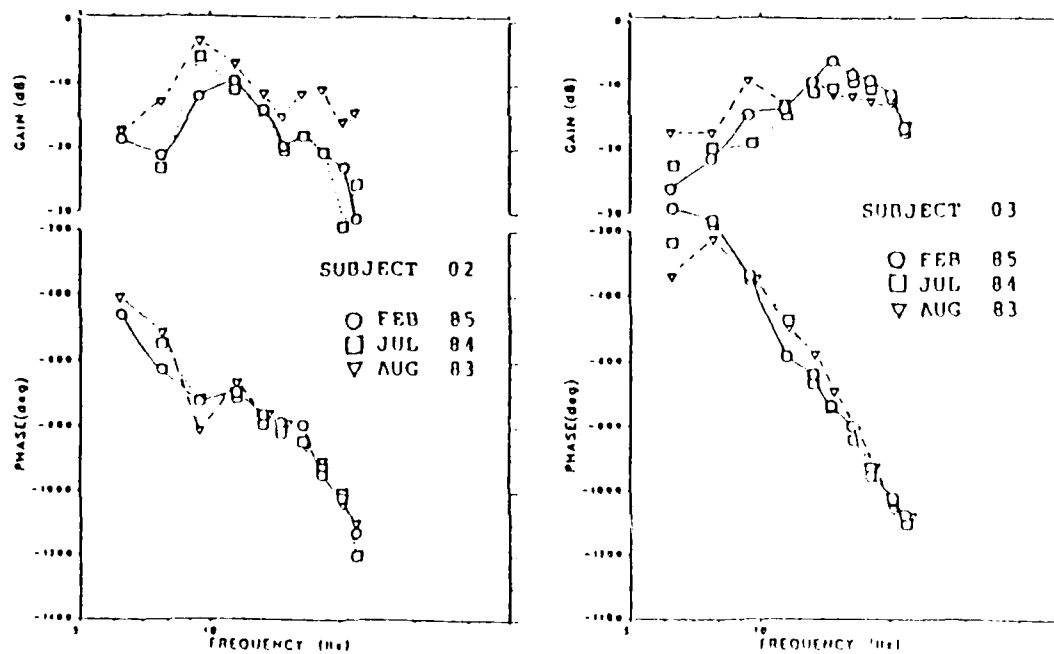
Figure 4.10.   Repeatability of the visual-cortical evoked response illustrated by describing function gain and phase values for 2 subjects over a 3 year span.

Section 4.3   Repeatability Of The Measure

Measurements were obtained over a three year period
from two subjects in which the same SOS input frequencies
and stimulus parameter values were used.   This was for the
lights-only condition.   Thus the question of the
repeatability of the SSVEP measure over time could be
explored.

The describing functions for each of the two subjects
are plotted in Figure 4.10.   Only mean responses are
plotted as the objective of these comparisons was to
explore the trends over time.   Most noteworthy are; on the
one hand the differences between the two subjects and on
the other, the way in which the general trends remain the
same for each subject over the three years.

Subject 02 typically exhibited strong driven alpha
activity as indicated by the peaking of the describing
function gain at 9.49 Hz.   This gain peaking was the
smallest for the Feb 85 period.   A drop in gain in the
beta region, above 14.76 Hz, when going from Aug 83 to Jul
84 can also be observed.   From personal communication with
Subject 02, she indicated "boredom" associated with the
task of looking at the flickering lights.   In fact, Feb 85
was the last time during which data was collected from
this subject, as soon after she terminated employment with
the Laboratory and returned to academia.   These findings
are presented here to make the reader aware of one of the

possible problems and simultaneously one of the uses of
this measurement technique. Obviously, it is sensitive to
attention and motivation, especially in the alpha region,
for some subjects. This can be both an advantage and a
limitation of the measure. More will be said about this
issue in Section 4.4.

Section 4.4   Steady State and Transient Comparisons

The primary analysis methodology used in this report
is based upon linear system performance, with an
additional ability to consider the background or remnant
response. Therefore an important question to be
considered is, to what extent is the visual cortical
response system linear. As discussed earlier (Section
3.2), if a system is linear and time invariant, the
resulting transfer function obtained would be independent
of the method of stimulation. For the visual evoked
system there are two ways in which an evoked response can
be obtained; through steady-state stimulation, and through
transient stimulation. An investigation into the
relationship of the describing functions obtained by both
methods of stimulation was undertaken.

The methods used for stimulus generation and analysis
are discussed in Sections 3.2 and 3.6. In order to make
comparisons, either the steady-state response, which is a
frequency measure, had to be transformed into the time
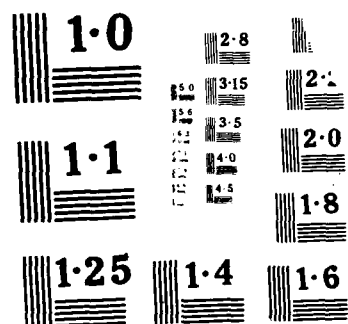
domain, or the transient response, obtained as a time locked average, had to be transformed into the frequency domain. Going from the SOS frequency response to the time domain requires first fitting a model to the 10 frequency measures, and then computing the transient response of the model to a pulse input. Going from the transient response to the frequency domain requires discrete Fourier transformation of the time-locked averages of the pulse stimuli and the EEG response. The latter method required no model interpretation for transformation and therefore was chosen as the approach to use.

There was one problem encountered when generating the transient stimulus for later comparison purposes. As mentioned in Section 3.2, one advantage of using a SOS stimulus is that power can be concentrated at discrete frequencies in the frequency domain. A time domain pulse input, on the other hand, is equivalent to continuous power in the frequency domain. For comparisons, the pulse used for transient stimulation was chosen to contain a flat spectrum of power over the same frequency range as spanned by the SOS input. However, it was not possible to achieve the same power levels at frequencies of interest for the transient input as used for the steady-state input. Using close to maximum pulse strength for the transient stimulus produced power levels in the frequency domain that were approximately 10 dB less than the concentrated steady-state power levels used. For

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comparison purposes therefore, transient describing
function gains were shifted up by 10 dB in the following
describing function plots. Again, this was done because
the transient input was 10 dB less than the corresponding
SOS input. Spreading power equally over the frequency band
in the case of the transient stimulus meant that it was
actually much stronger overall as compared to the steady-
state stimulus.

Transient data were collected from subjects at the end
of the same sessions in which steady-state data were
collected. Transient data was collected for four trials
of lights only (no task load) and then for four trials in
which subjects performed a grammatical reasoning task
(task loading). In this section comparisons between the
transient and steady-state lights only conditions are
made. In Section 5.2 the effects of task loading on the
transient and steady-state conditions are considered.

Average time responses to the transient stimulus are
plotted for four subjects in Figure 4.11. The shapes of
responses compare favorably with others reported in the
literature (O'Donnell, 1979, p15). The similarities and
differences between the four subjects' responses are
noteworthy. Each subject's response exhibited different
amounts of 'ringing' to the pulse stimulus. The strength
of the ringing was related to the magnitudes of the
component amplitudes across the time axis. Subject 02
exhibited perhaps the most, and Subject 15 the least.

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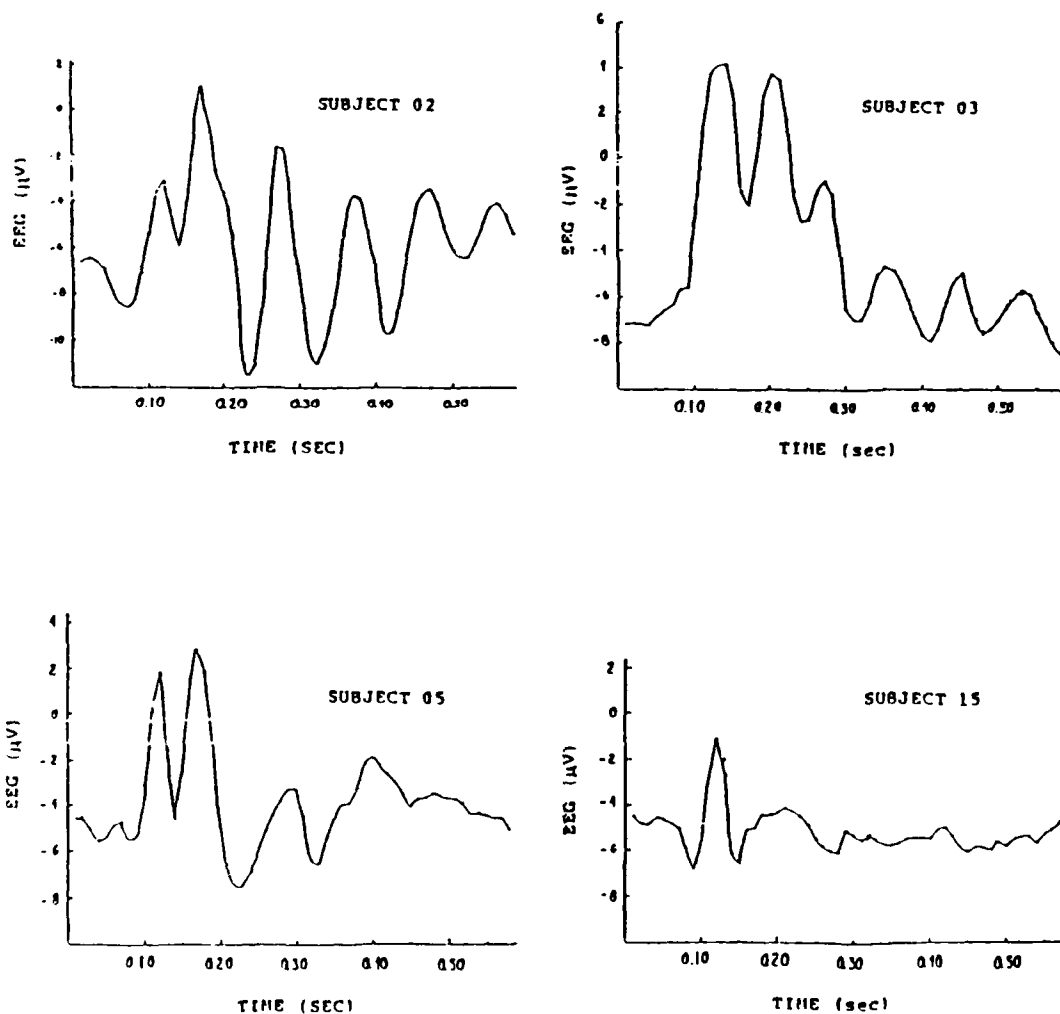
Figure 4.11. Time-lock averaged time responses to transient stimulation for 4 subjects.

For all subjects the first strong component occurred approximately 100 milliseconds after stimulus onset.

Describing functions computed from transformations of the transient time averages are plotted for the same four subjects in Figure 4.12. Subject 02, with the most ringing, had the largest peak gain response centered around 10 Hz. A 'dropout' response at approximately 15 Hz was also present. Subject 03, who exhibited less ringing, exhibited a peak response at approximately 13 Hz. This could be considered an upper alpha frequency resonance. Subject 05, who exhibited less ringing yet, had a 'flat' response between 7 Hz and 11 Hz. This might still be considered an alpha like response however. Subject 15, who had the least amount of ringing, demonstrated a slight peak at 10 Hz, and a low gain response below this frequency. Above 10 Hz, this subject's response was resonably flat up to 20 Hz.

In Figure 4.13, describing functions resulting from both transient and steady-state stimulation are plotted together for the four subjects. These are from the lights only (no task) condition. For Subject 02, the driven alpha peak and the dropout point are in the same frequency locations for both the transient and steady-state describing functions. Above 10 Hz, the phase curves match closely. For Subject 03, there is similar peaking in the upper alpha range (13.25 Hz), and both phase curves follow similar trends. The alpha TEP gain response of Subject 05
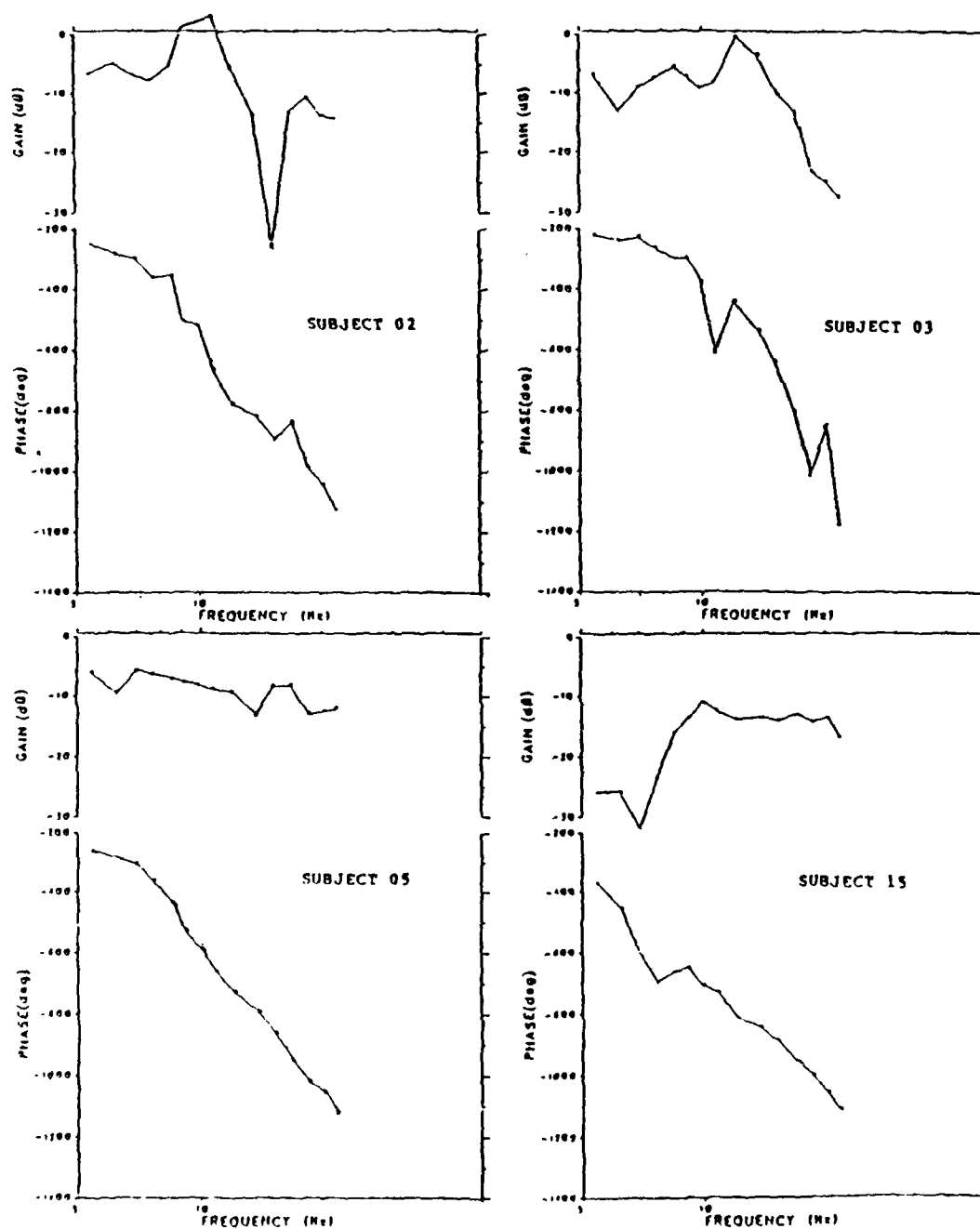
Figure 4.12. Describing functions resulting from frequency transformation of Figure 4.11 time averages.
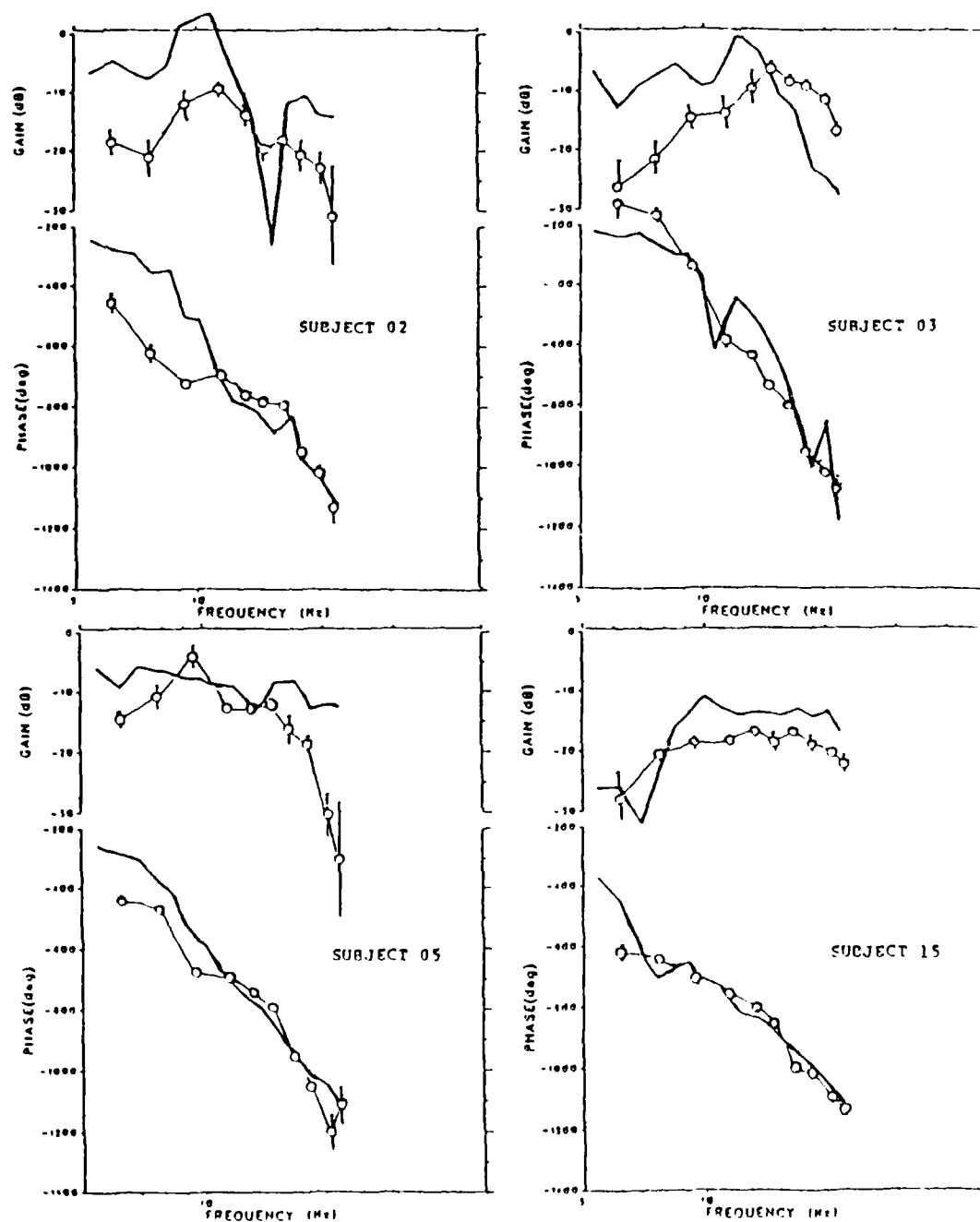
Figure 4.13.   Steady-state (circles), and transient
               (thicker lines) describing functions.
               Transient data is reproduced from Figure
               4.12.

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corresponds to the SSEP alpha peaking. The phase curves are close between 11.5 Hz and 18.25 Hz. Where the TEP gain response is stronger than the SSEP response, there is less phase lag. This is observable for both Subjects 02 and 05. For Subject 15 the gain curves exhibit similar shapes as do the phase curves.

For Subject 02, the trends observable in the transient and steady-state gain curves are similar (Figure 4.13). The alpha band peak, however, is significantly larger in the transient stimulation condition. This experimental session was the same one as discussed in Section 4.3, in which the subject experienced "boredom" during the steady-state condition. This Subject had been exposed to the steady-state stimulus a number of times over a three year period (Figure 4.10). Transient stimulation, on the other hand, was a relatively new experience for Subject 02 at that time. This data further illustrates the effects of attention on the resonant properties of the gain response.

Results of this investigation into transient and steady-state stimulation of the visual-cortical response system provided a number of useful observations. The strength of the time domain component amplitudes related to the frequency domain gain responsiveness. Greater amplitudes in the time domain corresponded to more peaking in the frequency domain. This was to be expected for a linear system, as it related to the damping of the system

in both cases. Transient and steady-state frequency responses appeared comparable for each subject. The differences in responses across subjects indicated the need to consider each subject separately.

Is the visual-cortical response system linear? Certainly not, however, the comparable results across the two modes of stimulation, unique to each subject, indicate that it is 'somewhat' linear. By this it is meant that the general shapes are similar. The differences are probably due to such things as the fact that the two inputs had different power levels, and that the degree of attention may mediate overall system response, especially in the alpha frequency range. The relationship between transient and steady-state responses is further considered in Section 5.2 of this report, where the two responses are compared across task loading conditions.

5. EFFECTS OF TASK LOADING

Three tasks, requiring various levels of visual, mental and motor processing, were used to elicit diverse cognitive states with the intention of evoking different visual-cortical responses.

The first task considered in this section is manual tracking. This task was used along with the lights-only condition in an investigation of visual stimulus parameters. Results from that study, comparing manual tracking to lights-only, are presented in Section 5.1.

The grammatical reasoning task was performed during both steady-state and transient stimulation of the visual-cortical system. Comparisons between lights-only and grammatical reasoning are presented for both modes of stimulation in Section 5.2.

A study was undertaken in which three conditions, presented in a balanced order, were explored. The three conditions were: lights-only, manual tracking, and grammatical reasoning. The results from that study are described in Section 5.3.

Early in the development of the experimental methodology, data was collected from two subjects across the conditions of: lights-only, manual tracking and, supervisory control. These results, reported in Section 5.4, provide insights into relationships that exist among the three conditions tested and the data of Section 5.3.

For the visual-cortical evoked response to be a
useful measure of cognitive load, it must be sensitive to
changes in levels of difficulty within tasks, as well as
to changes across tasks. Therefore, two levels of
supervisory control task difficulty were considered in
Section 5.5. Ways in which the visual-cortical evoked
response measure was and was not sensitive to levels of
task difficulty are presented in this last Section.

5.1 Manual Tracking Effects

As part of the stimulus parameter study, reported in
Section 4.2, subjects performed the manual tracking task
described in Section 3.4. This was done for two reasons;
to provide variety for the subjects in the experimental
session, and to obtain tracking data. Due to the number
of nontracking conditions required, fewer tracking
conditions were performed to reduce each experimental
session to a reasonable length of time. Thus the
conditions tested were tracking and no-tracking for one
depth of modulation (the greater of the two, 13%) and two
intensities (80 ft-L and 40 ft-L). The findings of
Section 4.2, as did preliminary data, indicated that the
higher depth of modulation produced a stronger evoked
response, thus the 13% depth of modulation was used.

The same dependent variables were analyzed for
tracking/no-tracking effects as in Section 4.2. They

were: CORrelated EEG Power (CORP), REMnant (REM), and describing function GAIN (GAIN). The independent variables were stimulus INTensity (INT), FREQuency (FREQ), TRACKing task (TRACK), and Subjects (Ss). The variable TRACK was the presence or absence of the tracking task. Once the spectra and dependent variables were computed, the data was collapsed or averaged across all runs for each subject per condition. Separate analyses were then performed for each of the dependent variables.

5.1.1 Effects on CORP

To assess the effects of tracking on CORP a 3-way ANOVA was conducted with the factors being; INT, FREQ, and TRACK. Table 5.1 is the resultant ANOVA summary table.

These results are consistent with the previous ones reported in Section 4.2.1, in that the main effect of INT was not significant ($p > .1$) and the main effect of FREQ was significant ($p < .01$). A review of the raw data revealed the same basic bandpass characteristics as reported in Section 4.2.1.

In addition, the main effect of TRACK was observed to be significant ($p < .05$). Table 5.2 lists CORP vs TRACK. It can be seen that adding the cognitive demands of the tracking task resulted in a slightly increased CORP. It can be hypothesized that this change was due to an overall increase in the responsiveness of the visual-cortical

TABLE 5.1   ANOVA summary, effects on CORP

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
INT	1	1.0455	0.32	0.5827
FREQ	9	582.7500	20.12	0.0001
TRACK	1	25.0860	7.79	0.0210
INT*FREQ	9	33.3499	1.15	0.4186
INT*FREQ	1	4.3054	1.34	0.2772
FREQ*TRACK	9	28.3491	3.98	0.5125

TABLE 5.2   Effects of Tracking on CORP

CORP (dB)		Effect of
No-Tracking	Tracking	Tracking
-38.79	-37.20	+1.59

TABLE 5.3   ANOVA summary, effects on CORP, with Ss

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
Ss	9	6465.9103	26.03	0.0001
INT	1	10.4551	0.38	0.5388
FREQ	9	5827.5003	23.46	0.0001
TRACK	1	250.8600	9.09	0.0028
Ss*INT	9	437.9084	1.76	0.0751
Ss*FREQ	81	10807.8020	4.83	0.0001
Ss*TRACK	9	837.6916	3.37	0.0007
INT*FREQ	9	333.4996	1.34	0.2143
INT*TRACK	1	43.0541	1.56	0.2128
FREQ*TRACK	9	283.4019	1.14	0.3335

TABLE 5.4   Effects of TRACK on CORP, by Subject

Subj #	CORP (dB)		Change due to
	No Tracking	Tracking	Tracking
01	-35.07	-35.90	-0.83
02	-40.52	-36.83	+3.69
03	-39.02	-35.58	+3.44
05	-32.07	-32.06	+0.01
07	-42.93	-44.16	-1.23
08	-47.04	-39.17	+7.87
09	-43.00	-41.16	+1.84
10	-35.09	-36.99	-1.90
14	-31.51	-32.10	-0.59
15	-41.53	-38.05	+2.48

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system during manual tracking. No other significant effects were observed.

To assess the effects of individual differences the analysis was redone with the added factor of subjects. That is, a 4-way ANOVA was conducted with the major factors being; Ss, INT, FREQ, and TRACK. The results are summarized in Table 5.3.

The findings are as expected in that: (1) The main effect of Ss was significant ($p < .01$) (i.e. individual differences are important); (2) The main effect of INT was not significant ($p > .10$); (3) The main effect of FREQ was significant ($p < .01$) (i.e. a consequence of the bandpass characteristics); (4) The main effect of TRACK was significant ($p < .01$); and (5) The interaction of Ss and FREQ was significant ($p < .01$) (i.e., differences in individual bandpass characteristics). Furthermore, the interaction of Ss and TRACK was found to be significant ($p < .01$).

Table 5.4 lists CORP vs TRACK for all 10 Ss. This table demonstrates that the significant interaction of Ss with TRACK is a consequence of some subjects showing an increased CORP response when the tracking task was added, while others responded just the opposite. Such inconsistencies clearly illustrate the need to consider individual differences. No other significant effects were observed.

5.1.2 Effects on Remnant

To assess the effects of tracking on REM, a 3-way ANOVA was conducted with the factors being; INT, FREQ, and TRACK. Table 5.5 is the resultant ANOVA summary table.

These results support the previous findings of Section 4.2.2. That is, the effect of INT was not significant ($p > .10$), while the effect of FREQ was significant ($p < .01$) and was due to the differential remnant response across the spectrum. The main effect of TRACK was significant ($p < .01$). Table 5.6 indicates that this effect was due to an overall increase in REM when the tracking task was added. This supports the finding with CORP that the increased cognitive demands results in an increased level of EEG activity.

The interaction of FREQ and TRACK was also found to be significant. Table 5.7 shows that the differences in REM between the tracking and no-tracking conditions to be positive for the high frequencies and negative for the low frequencies. These findings are consistent with others reported in the literature (refer to Section 2.3), namely an increase in power in the beta band and a decrease in power in the alpha band with cognitive loading.

To assess the effects of individual differences, the analyses were redone with the added factor of subjects. The results are summarized in Table 5.8. The results are exactly as expected in that the main effects of Ss, FREQ,

TABLE 5.5   ANOVA summary table, effects on REM

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
INT	1	0.0008	0.02	0.8879
FREQ	9	112.9835	301.54	0.0001
TRACK	1	1.2267	29.47	0.0004
INT*FREQ	9	0.3730	1.00	0.5026
INT*TRACK	1	0.0004	0.01	0.9180
FREQ*TRACK	9	3.5585	9.52	0.0013

TABLE 5.6   Effects of Tracking on REM

| REM (dB) | | Effect of |
No-Tracking	Tracking	Tracking
-46.67	-46.32	+0.35

TABLE 5.7   Effects of Tracking on Remnant, across FREQ

| | REM (dB) | | Change due to |
FREQ (Hz)	No Tracking	Tracking	Tracking
6.25	-49.66	-49.68	-0.02
7.73	-48.81	-49.13	-0.32
9.49	-43.57	-44.36	-0.79
11.49	-44.65	-44.78	-0.13
13.25	-46.52	-46.23	+0.29
14.74	-46.82	-46.07	+0.75
16.49	-47.80	-46.74	+1.06
18.25	-46.90	-45.93	+0.97
20.23	-45.64	-44.86	+0.78
21.74	-46.32	-45.46	+0.86

TABLE 5.8   ANOVA summary, effects on REM, with Ss

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
Ss	9	2663.5326	368.62	0.0001
INT	1	0.0087	0.01	0.9169
FREQ	9	1129.8354	156.36	0.0001
TRACK	1	12.2670	15.28	0.0001
Ss*INT	9	41.7772	5.78	0.0001
Ss*FREQ	81	1653.5423	25.43	0.0001
Ss*TRACK	9	175.9925	24.36	0.0001
INT*FREQ	9	3.7300	0.52	0.8630
INT*TRACK	1	0.0046	0.01	0.9393
FREQ*TRACK	9	35.6854	4.94	0.0001

and TRACK were significant (p < .01) as well as the interactions between Ss and INT, FREQ, and TRACK. These interactions were a consequence of inconsistencies in directions of responses between subjects and not simply differences in the magnitude of responses.

5.1.3 Effects on GAIN

To assess the effects of tracking on GAIN, a 3-way ANOVA was conducted with the factors being; INT, FREQ, and TRACK. The results are summarized in Table 5.9.

The main effect of all 3 factors was found to be significant (p < .01). Table 5.10 lists GAIN vs INT. It demonstrates that as INT increased, GAIN decreased. This was consistent with the findings noted in Section 4.2.3. The effect of FREQ is a reflection of the bandpass characteristics of the system (similar to results of GAIN vs FREQ plotted in Figure 4.6). Table 5.11 lists GAIN vs TRACK. It shows that the increased cognitive demands of the tracking task resulted in an overall increase in GAIN. This is consistent with the previous findings for CORP and REM which indicated similar increases in the level of EEG activity when the tracking task was employed. Since the input was the same across tracking and no-tracking conditions, an increase in GAIN was a consequence of an increase in CORP.

Finally, to assess the effects of individual differences, the ANOVA was redone with the added factor of

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TABLE 5.9 ANOVA summary table, effects on GAIN

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
INT	1	219.0567	444.47	0.0001
FREQ	9	251.0197	56.59	0.0001
TRACK	1	7.1372	14.48	0.0042
INT*FREQ	9	7.1059	1.60	0.2468
INT*TRACK	1	1.2991	2.64	0.1389
FREQ*TRACK	9	3.0612	0.69	0.7053

TABLE 5.10 Effects of INT on GAIN

GAIN (dB)		Effect of INT
@ 40 ft-L	@ 80 ft-L	Increase
-17.40	-22.08	-4.68

TABLE 5.11 Effects of TRACK on GAIN

GAIN (dB)		Effect of
No-Tracking	Tracking	Tracking
-20.16	-19.32	+0.84

TABLE 5.12 ANOVA summary, effects on GAIN, with Ss

SOURCE	DF	TYPE 1 SS	F VALUE	PR > F
Ss	9	3499.7822	91.49	0.0001
INT	1	2190.5676	515.39	0.0001
FREQ	9	2510.1974	65.62	0.0001
TRACK	1	71.3729	16.79	0.0001
Ss*INT	9	1084.5496	28.35	0.0001
Ss*FREQ	81	3865.1782	11.24	0.0001
Ss*TRACK	9	117.5602	3.07	0.0017
INT*FREQ	9	71.0593	1.86	0.0583
INT*TRACK	1	12.9915	3.06	0.0818
FREQ*TRACK	9	30.6124	0.80	0.6175

Ss. The results are summarized in Table 5.12. The results are as expected in that all 4 main effects were found to be significant ($p < .01$) as well as all three 2-way interactions between Ss and INT, FREQ, and TRACK ($p < .01$). Again, the main effect of Ss indicates the importance of individual differences. A review of the raw data indicated that the main effect of FREQ and its' interaction with Ss were basically a consequence of the bandpass characteristics and differences in individual frequency responses as previously observed.

Table 5.13 is a tabulation of GAIN vs TRACK for each Ss. The table clearly demonstrates that the interaction of Ss and TRACK is primarily a consequence of inconsistencies and not differences in magnitude. Thus the main effect of TRACK is not reliable across subjects. No other significant effects were found.

5.1.4 Summary of Effects

A consistent trend of increased response in CORP, REM, and GAIN with tracking was measured. It could be hypothesized that this trend was a result of an overall increase in the responsiveness of the visual-cortical system due to cognitive loading. In terms of REM, this trend was manifest as a decrease in response power in the alpha band and an increase in the beta band across subjects. CORP and GAIN changes were not as consistent as REM changes across subjects, indicating the importance of

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TABLE 5.13 Effect of TRACK on GAIN, by Subject

| Subj # | GAIN (dB) | | Effect of |
	No Tracking	Tracking	Tracking
01	-22.65	-22.63	+0.02
02	-19.67	-18.69	+0.98
03	-19.62	-18.23	+1.39
05	-15.48	-15.71	-0.23
07	-23.58	-23.19	+0.39
08	-22.87	-19.34	+3.53
09	-22.61	-22.00	+0.61
10	-17.82	-18.24	-0.42
14	-14.49	-13.86	+0.63
15	-22.82	-21.27	+1.55

considering each subject separately. Due to these find-
ings and those of Section 4.2, the remaining investiga-
tions reported include individual subject responses.

5.2   Grammatical Reasoning Effects

Data were collected from subjects performing the
grammatical reasoning (GR) task and during lights-only
(LO) for steady-state and transient light stimulation.
Steady-state stimulation was performed first, with a
random mix of task and lights-only conditions. Transient
data was collected at the end of the same sessions in
which steady-state data was collected. Data was collected
for four trials of lights-only and then for four trials in
which subjects performed the grammatical reasoning task.
This order had to be followed due to hardware limitations
of the experimental apparatus.

Results of task loading during steady-state
stimulation are considered in Figure 5.1 for the four
subjects. Data represent the averages from six 40.96 sec
replications for each condition for each subject. Standard
error about the mean is represented by vertical lines at
each data point on the plots. No error bars indicate that
the error was smaller than the symbol width used at that
frequency data point. Note the 'signature' of each pair
of describing functions for each subject. The effects of
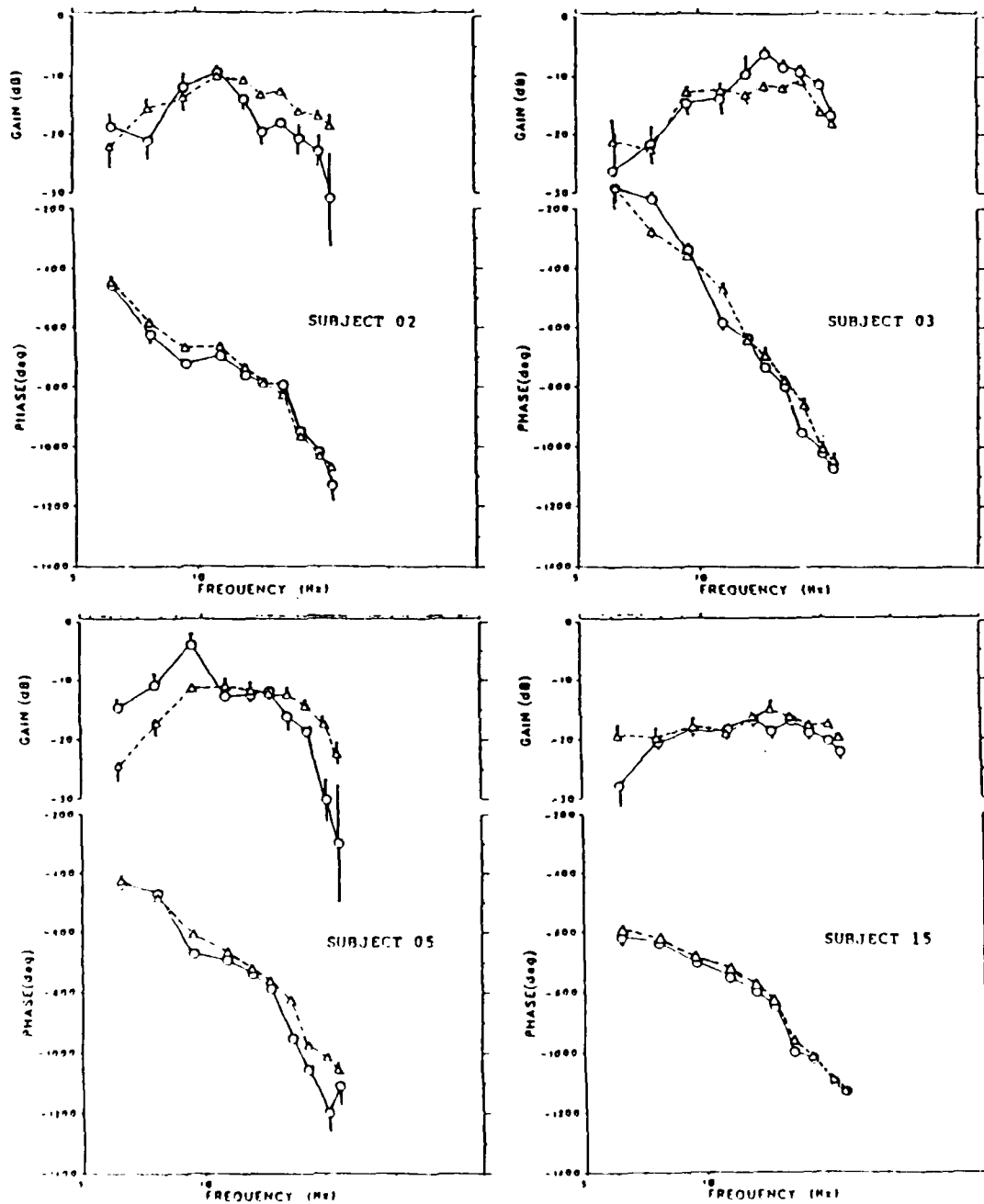task loading seem to be related to this signature.

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Figure 5.1. Steady-state describing functions, two
conditions: lights-only (circles), and
grammatical reasoning (triangles).

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Subject 05 exhibited a large resonant peak at 9.49 Hz (within the alpha band), which significantly decreased during task loading. There was a commensurate decrease in steepness of the phase curve about this frequency. These properties, using a systems engineering analogy, are suggestive of a change in the damping coefficient of an equivalent complex-conjugate pole pair in the visual-cortical system. Subject 02 also exhibited alpha band resonance properties. Unlike Subject 05, however, there was an increase in gain with task loading at the higher frequencies (above 12 Hz, within the beta band) without gain reduction in the alpha band. Subject 03 responded with a 14.74 Hz resonance for the LO condition. With task-loading, Subject 03 exhibited a gain reduction in the beta band in a manner similar to what was found for Subject 05 in the alpha band. Only minor changes were exhibited by Subject 15, mainly as slight increases in higher frequency sensitivity during task performance.

From these results the following hypotheses can be formulated: Subjects who are high alpha responders (subjects with alpha band resonance, e.g. Subject 05) will show an alpha band decrement with task loading. Subjects that are non-alpha responders (lack the alpha resonance peak, e.g. Subject 15) will tend not to show this alpha band decrement with task loading. In addition, with task loading, subjects tend to show a beta band increment.

Considering transient results next, time-locked average responses to the pulse stimulus, for both lights-only and task loading are presented in Figure 5.2 for the four subjects. Strong effects from task loading, namely overall decreases in response peaks or components during task performance are present for Subjects 02, 03, and 05. An opposite trend, a slight increase in response peaks with task loading, can be seen for Subject 15.

As with the steady-state EP responses, it is again worth noting the uniqueness of each subject's response. Subject 02 exhibited large component amplitudes, the transient response of a lightly damped system. Subject 15, on the other hand, responded with very few peaks or components, that of a heavily damped sytem.

A discussion of transient EP analysis in Section 2.4.2 presented findings from other researchers in this area. These findings can perhaps be summarized as follows: inattention by distraction and increased perceptual-central processing demands resulted in reduction of the transient components at 100 msec, 200 msec and 300 msec. Perhaps this is an over simplification as many researchers would claim that there are independent effects observable at 100 msec and 300 msec after stimulus onset. The N100 component is reported to be affected by stimulus relevancy. The P300 is reported to exhibit reduction with increasing perceptual processing demands.

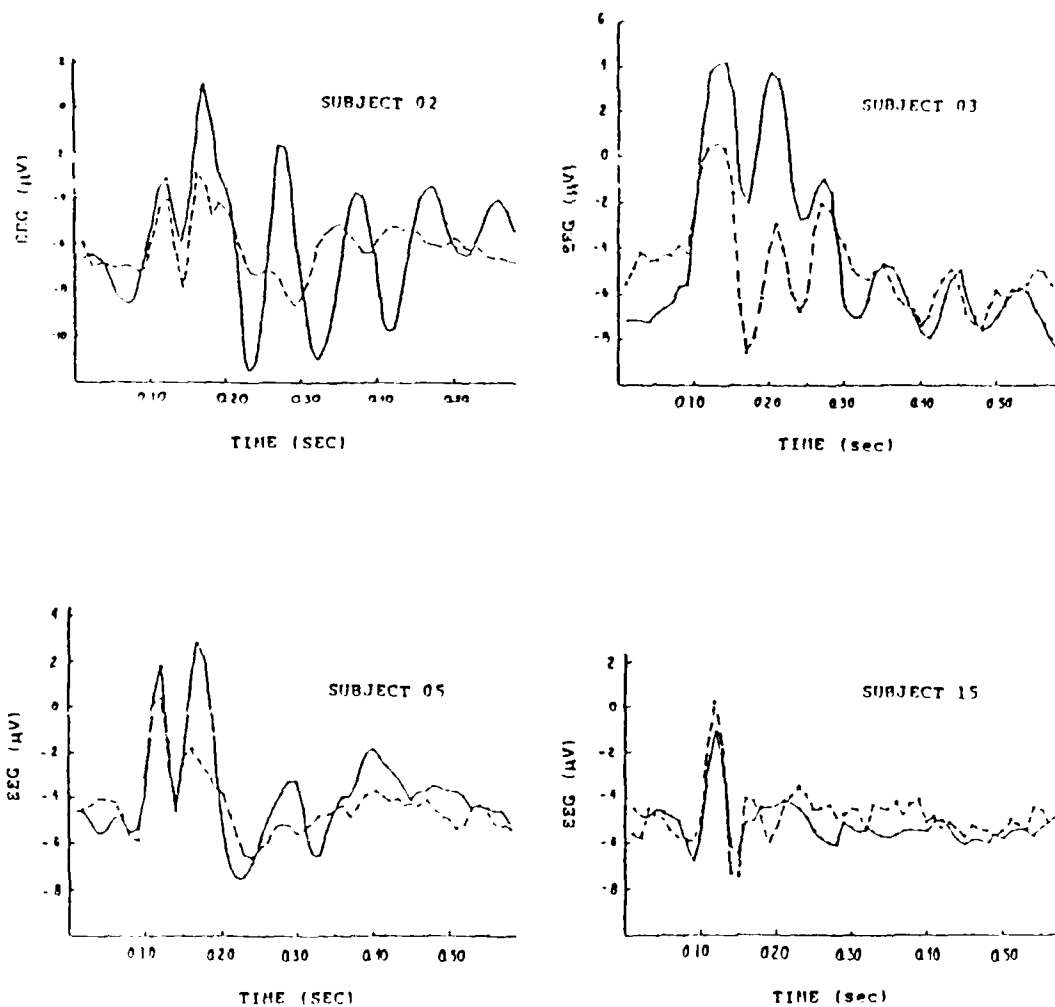For the experimental paradigm presented here,

Figure 5.2.   Time-lock averaged data, two conditions: lights-only (solid lines), and grammatical reasoning (dashed lines).

separation between stimulus relevancy and perceptual processing demands could not be made. The presence of the grammatical reasoning task demanded both increased perceptual processing and attention to the video display. Therefore, reduction in all components with task loading could be anticipated. In fact, 3 of the 4 subjects exhibited reductions in component values with addition of the cognitive task. Perhaps what is most striking is the unique way in which each of the three subjects manifested these reductions (Figure 5.2). Further, the fact that Subject 15 demonstrated the opposite effect might lead one to question the usefulness of looking solely at individual transient components, as opposed to taking a larger systems view, as an assay of workload.

The time-locked averages of Figure 5.2 were transformed into describing functions (Section 3.6), and plotted in Figure 5.3. Important relationships to observe are mappings between transient time average changes, related to task loading effects, and correspond- ing describing function changes. Subjects 02, 03, and 05, who exhibited component decrements in their average time responses with task loading, had concomitant decreases in their describing function gain curves. For Subjects 02 and 05 these gain reductions occurred most strongly below 13 Hz. For Subject 03, a similar gain reduction was demonstrated between 11 Hz and 14 Hz. Subject 15 exhibited the opposite trend of a gain increase below 8
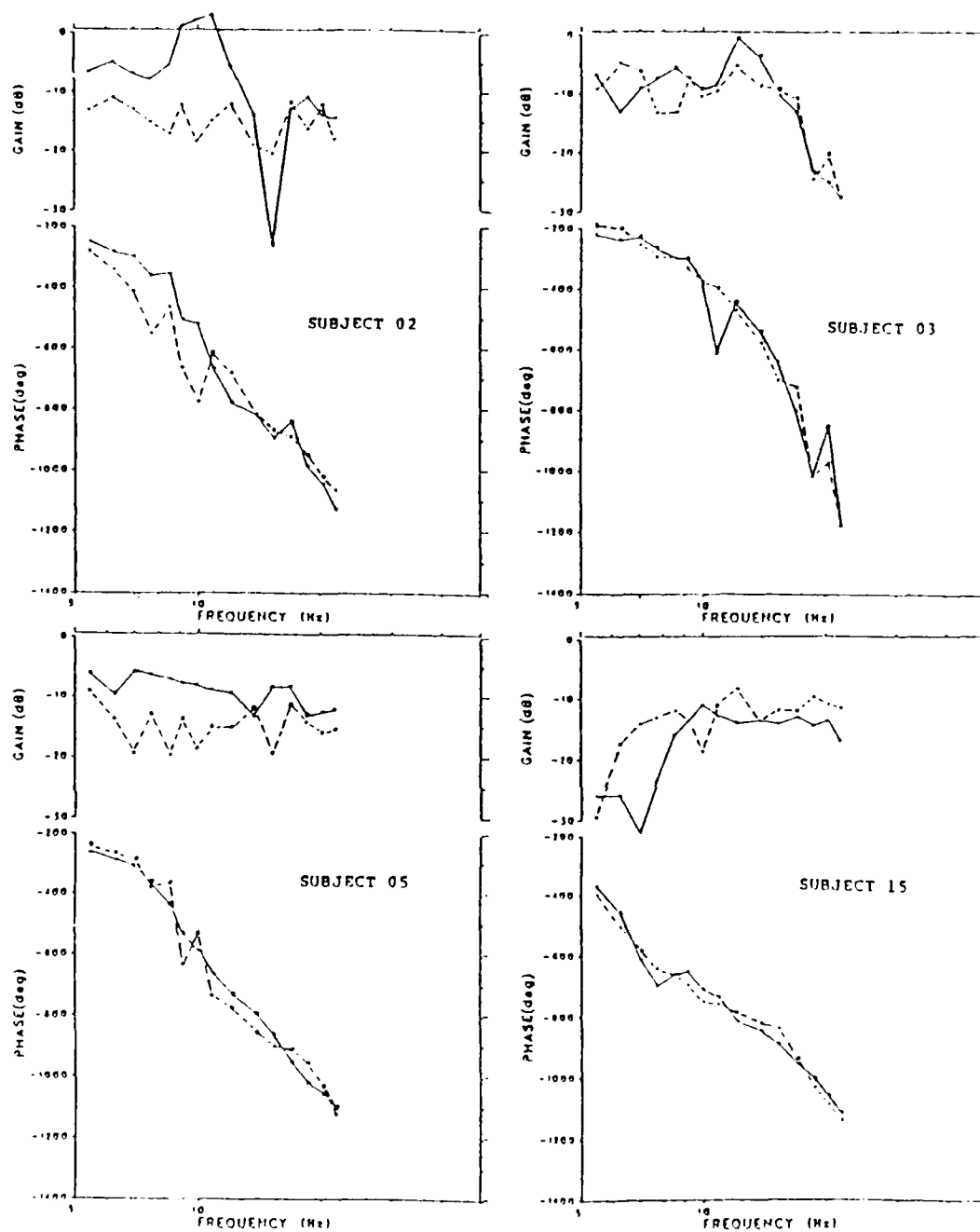
Figure 5.3. Transient describing functions from time
response data of Figure 5.2, lights-only
(solid lines), grammatical resoning (dashed
lines).

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Hz, between 10 Hz and 12 Hz, and above 14 Hz.

Relating these findings back to transient time history responses, large component changes (i.e. changes in ringing or damping) corresponded to changes in the resonant peaks in the frequency domain. The different responses depended upon where the Subject's resonance occurred (Subject 02 vs. Subject 03, for example).

Figure 5.4 shows, combined on each of four plots, GR and LO results for both transient and steady-state stimulation. The thicker solid lines and the thicker dashed lines are the TEP describing functions resulting from transient time averages (repeated from Figure 5.3). The circles and triangles represent the SSEP describing function values at each of the ten component frequencies from the SOS stimulation (repeat of Figure 5.1).

Correspondence between SSEP and TEP describing function curves are noteworthy. Describing functions for Subject 05 show corresponding regions of peak gain sensitivity for transient and steady-state stimulation (below 13 Hz), and show similar gain reduction with task loading in this same region. Subject 03 shows similar changes across stimuli in the 11 Hz to 16 Hz region of the gain curves. For both subjects, the effects of task loading in the regions of gain peaking or resonance are a reduction in the gain response.

The phase curves have a similar shape, across stimuli and across task conditions, for all subjects. Greatest

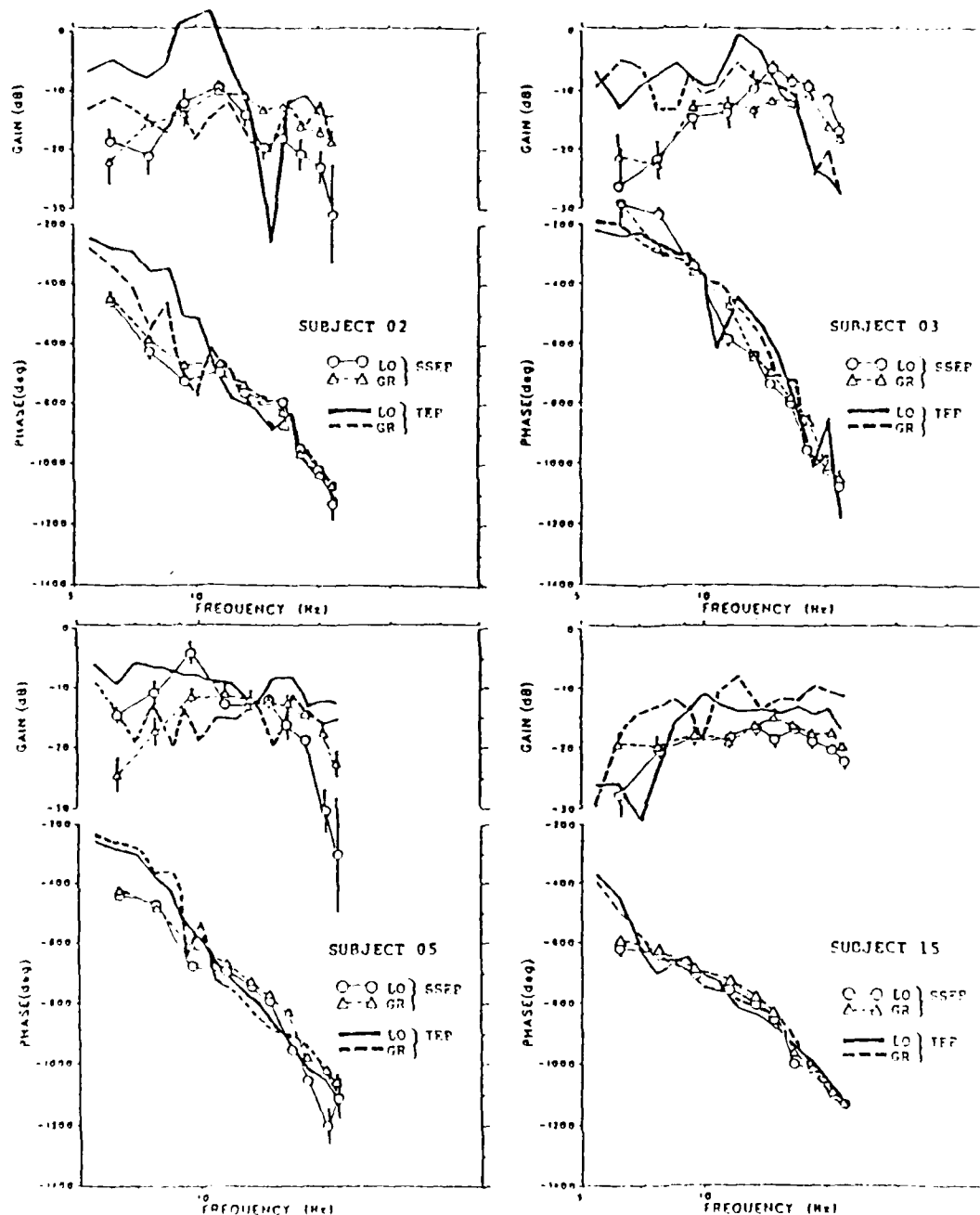Figure 5.4   Describing functions for transient and steady-
             state stimulation (Figures 5.1 and 5.3
             combined).   Transient; thick solid lines are
             lights-only, thick dashed lines are
             grammatical reasoning.   Steady-state; circles
             are lights-only, triangles are grammatical
             reasoning.

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differences occurred at points of resonance. A departure between gain curves for Subjects 02 and 05 (below 13 Hz), resulted in related differences in the phase curves.

The different responses across conditions for the two modes of stimulation for Subject 02 in Figure 5.4 are worthy of note. As discussed in Sections 4.3 and 4.4, this Subject was typically an alpha producer. The SSEP LO condition, however, did not demonstrate this, while the TEP response did. These differences are suggestive of differences in arousal and/or attention levels during exposure to the two stimuli for the LO condition. This was exhibited as lower gain responsiveness below 14 Hz and above 16 Hz. When the GR task was performed, on the other hand, gain responses for the two stimulation modes were quite similar. It is hypothesized that task loading was sufficiently engaging to increase the subject's attention level equally for both evoking stimuli.

To illustrate this point further, the SSEP describing function values of Figure 5.4 (which is reproduced in Figure 5.5a for Subject 02) were replaced by the describing function values from the conditions of Aug 83 (of Figure 4.10) and were plotted in Figure 5.5b. These comparisons suggest that changes in general arousal level and/or attention to a specific stimulus may be observable in SSEP and TEP describing functions.

As noted in Section 4.4, the SSEP and TEP inputs were designed to be similar. Due to the nature of the two
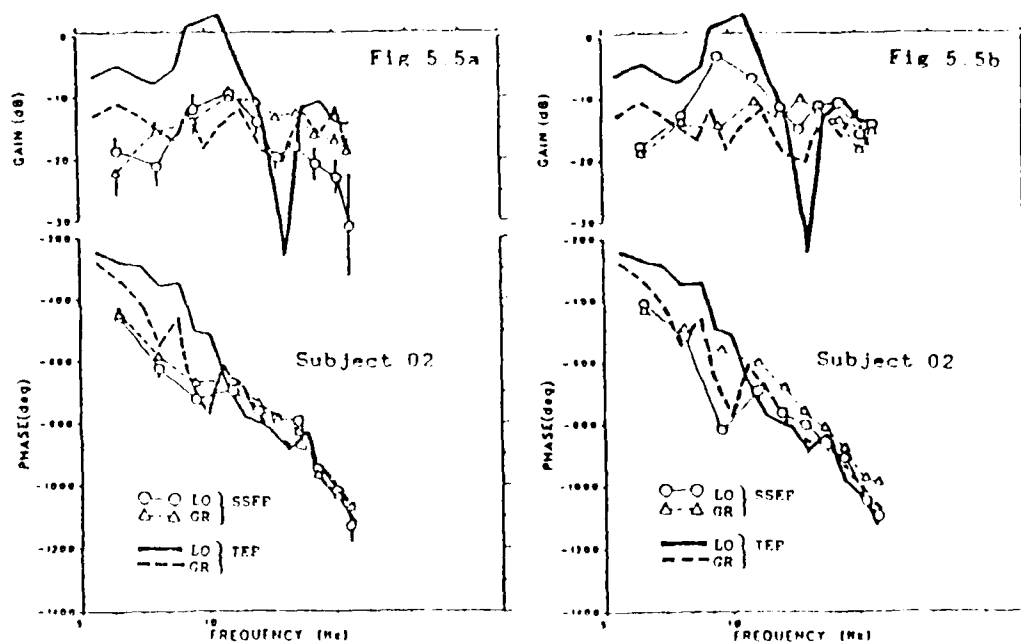
Figure 5.5   Illustration of possible effects of "arousal"
on the visual-cortical evoked response.
Figure 5.5a is a reproduction of Subject 02
response from Figure 5.4.   Figure 5.5b is the
same with   replacement of the steady-state
responses from Aug 83 (refer to Figure 4.10).

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stimuli, however, it was not possible to exactly achieve this objective. In considering comparisons between the TEP and SSEP describing functions, the reader must remember that the TEP stimulus was spread continuously over the frequency spectrum from 0 Hz to 30 Hz. The SSEP stimulus was concentrated at only 10 frequency locations. At points of resonance where the visual-cortical system is probably most sensitive to stimulus levels (recall the nonlinear response at 9.5 Hz of Figure 4.8) greater differences are to be expected.

In working with both transient and steady-state EP's, results indicate that it is useful to use both stimulation techniques. As hypothesized by Regan (1966), results do in fact complement one another. Describing functions obtained for this report by transient stimulation spanned a range from 0 Hz to 25 Hz. Thus they provided continuous spectral responses and could provide clues for phase unwrapping beginning at 0 Hz. In contrast, steady-state stimulation provides the ability to concentrate stimulus ⌐⌐ at selected frequencies. As a result, steady-state ⌐⌐ ulation yields evoked response measures in terms of scribing functions and background EEG measures (remnant s⌐ ctra) simultaneously.

5.3 Comparisons Across Grammatical Reasoning, Manual Tracking, and Lights-Only

For this section, three task loading conditions, provided in a balanced order, were explored. Most of the experimental data trials were performed with the evoking stimulus present. Half as many trials were conducted with no evoking stimulus present to analyze task effects on remnant with and with-out SSEPs present.

Data presented are from seven subjects (data for subjects 2,3,5 and 15 were the same as used elsewhere in this report). Each SSEP frequency response considered represents the average of from six to eight 40.96 sec. segments of electrocortical recordings. Averaging was performed as described in Section 3.6.1. Phase unwrapping was performed using the modeling approach of Section 3.6.3.

As indicated in Section 5.1, a complete picture of the effects of the cognitive loading on subjects can only be assessed if individual differences are considered. Thus the describing functions and remnant spectra for each of the 7 subjects investigated are plotted in Figure 5.6. A discussion of each subject's response follows.

5.3.1 Subject 02

Considering first the remnant spectra for Subject 02 in Figure 5.6, an alpha peak for the Lights-Only (LO)

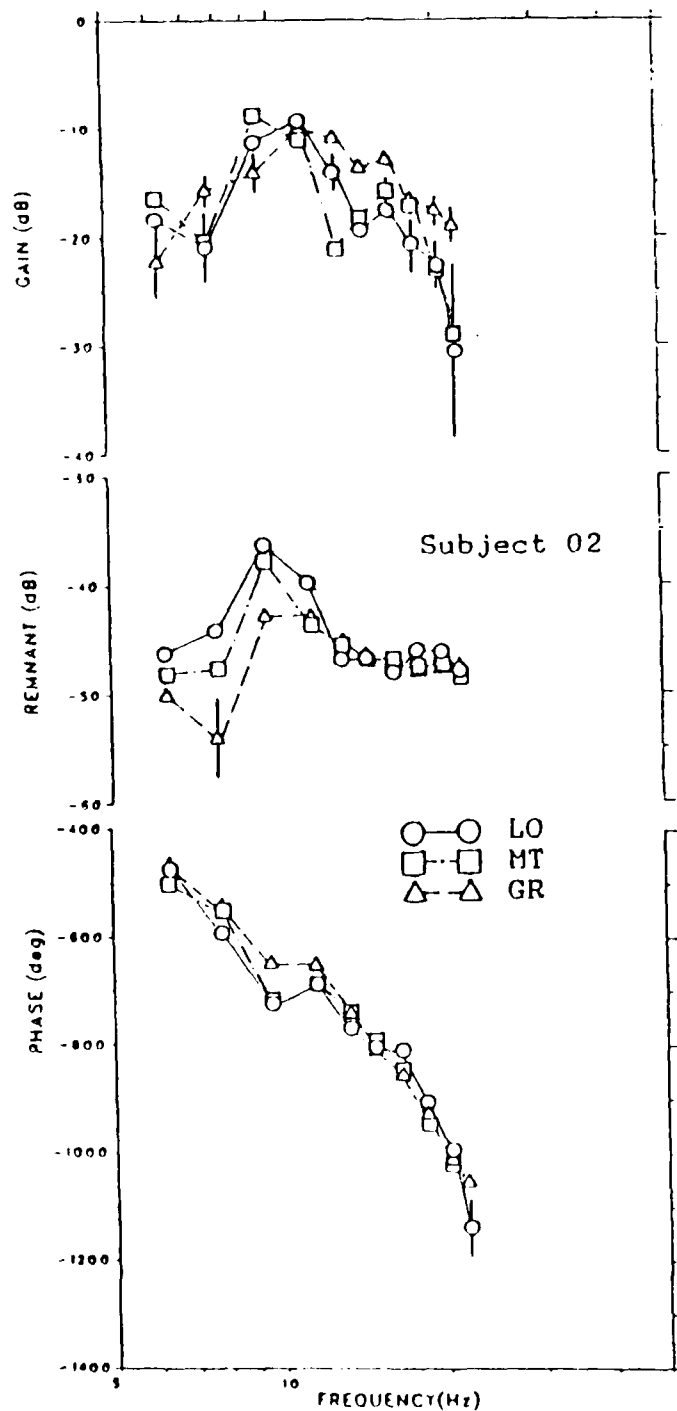Figure 5.6   Steady-state describing functions and remnant
spectra for subjects exposed to steady-state
stimulation across three conditions; lights-
only (circles), manual tracking (squares),and
grammatical reasoning (triangles).
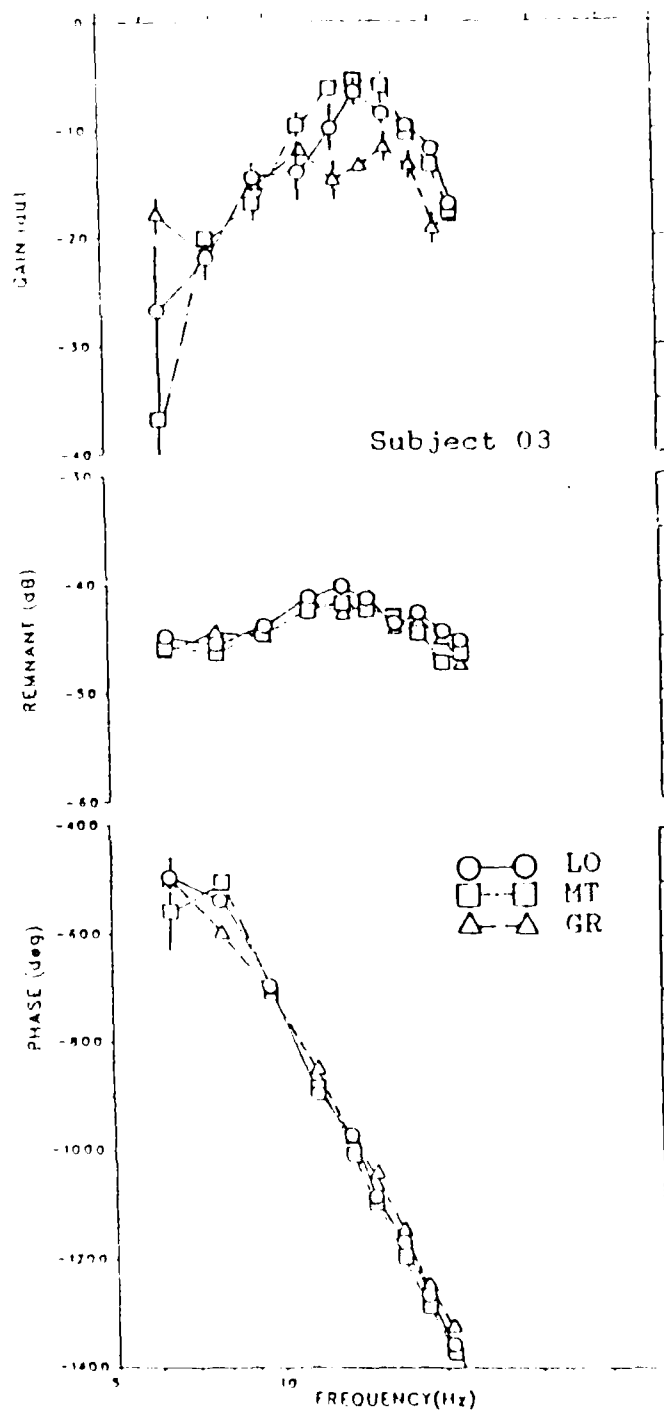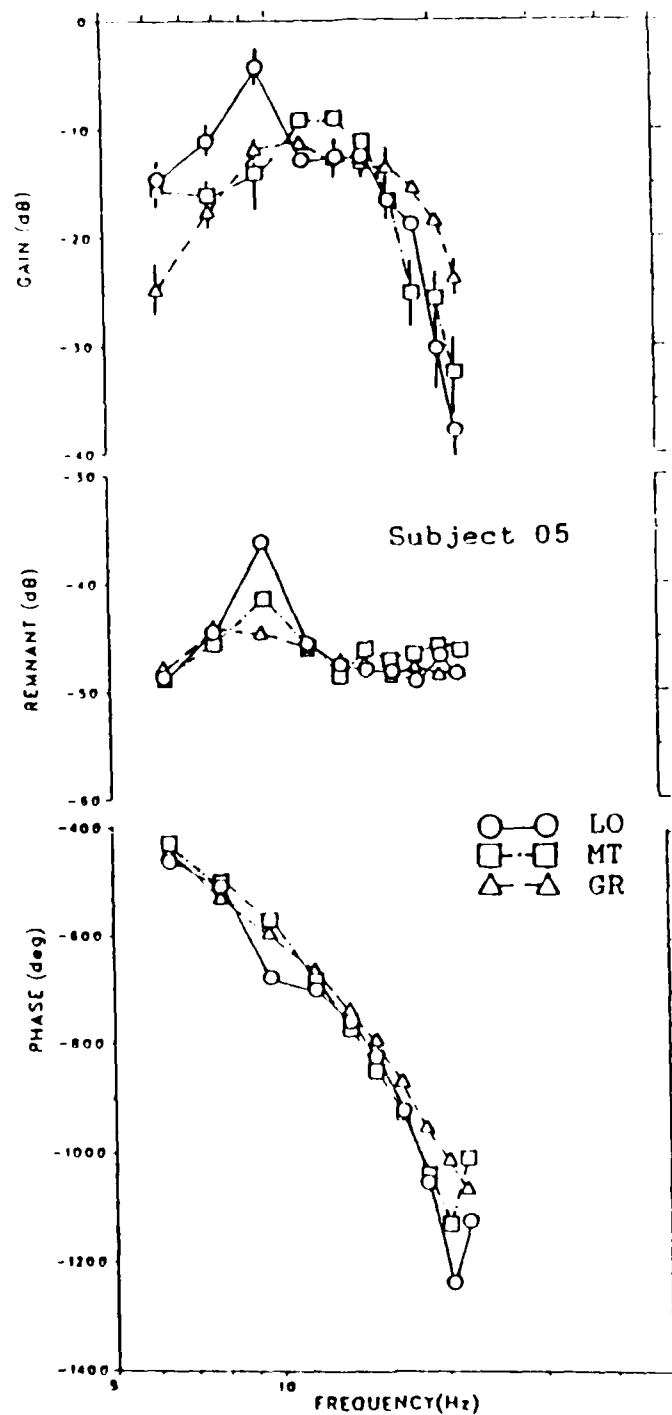
125

Figure 5.6   (Continued)

126

Figure 5.6   (Continued)

Figure 5.6   (Continued)

Figure 5.6 (Continued)

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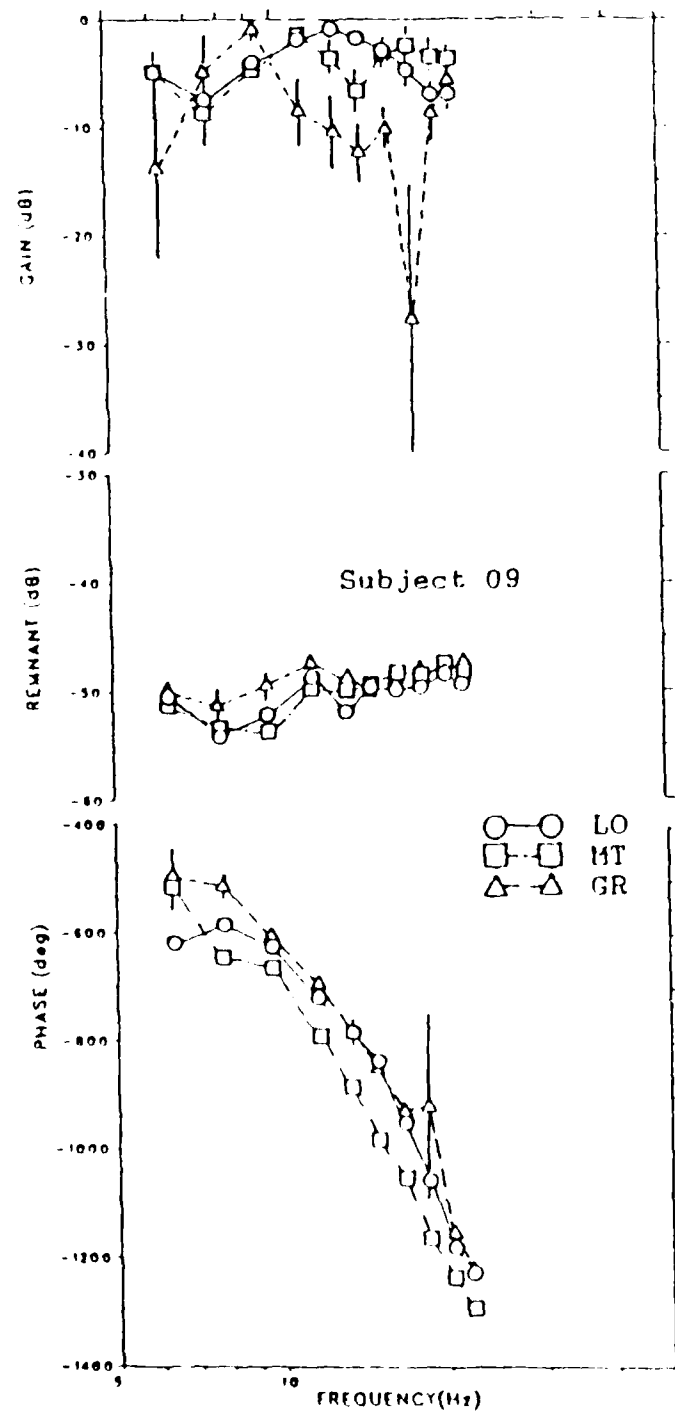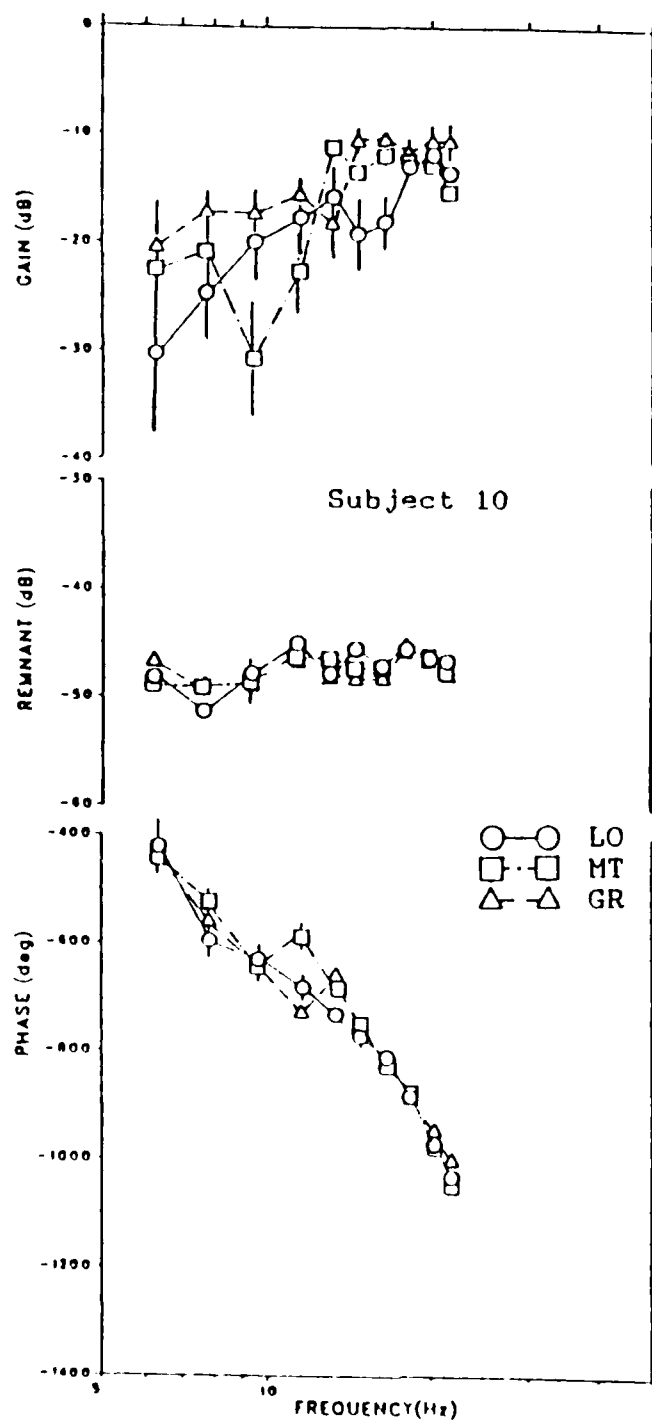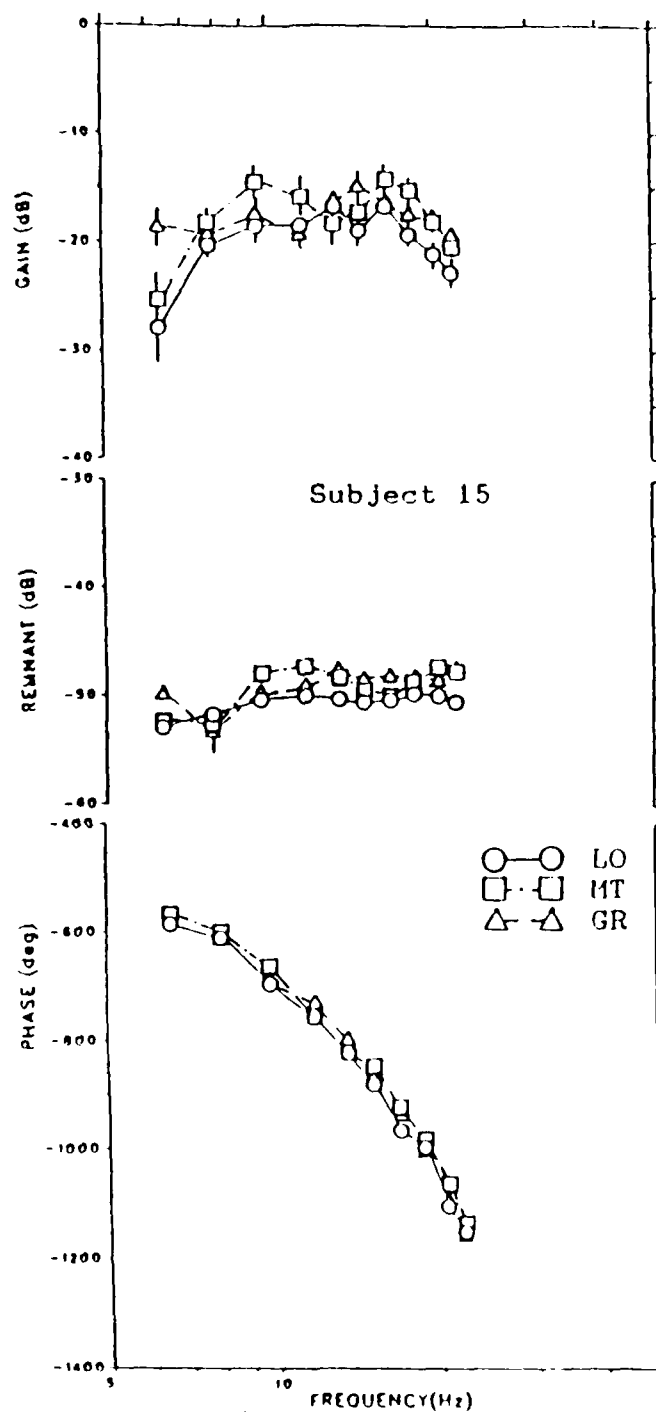
Figure 5.6   (Continued)
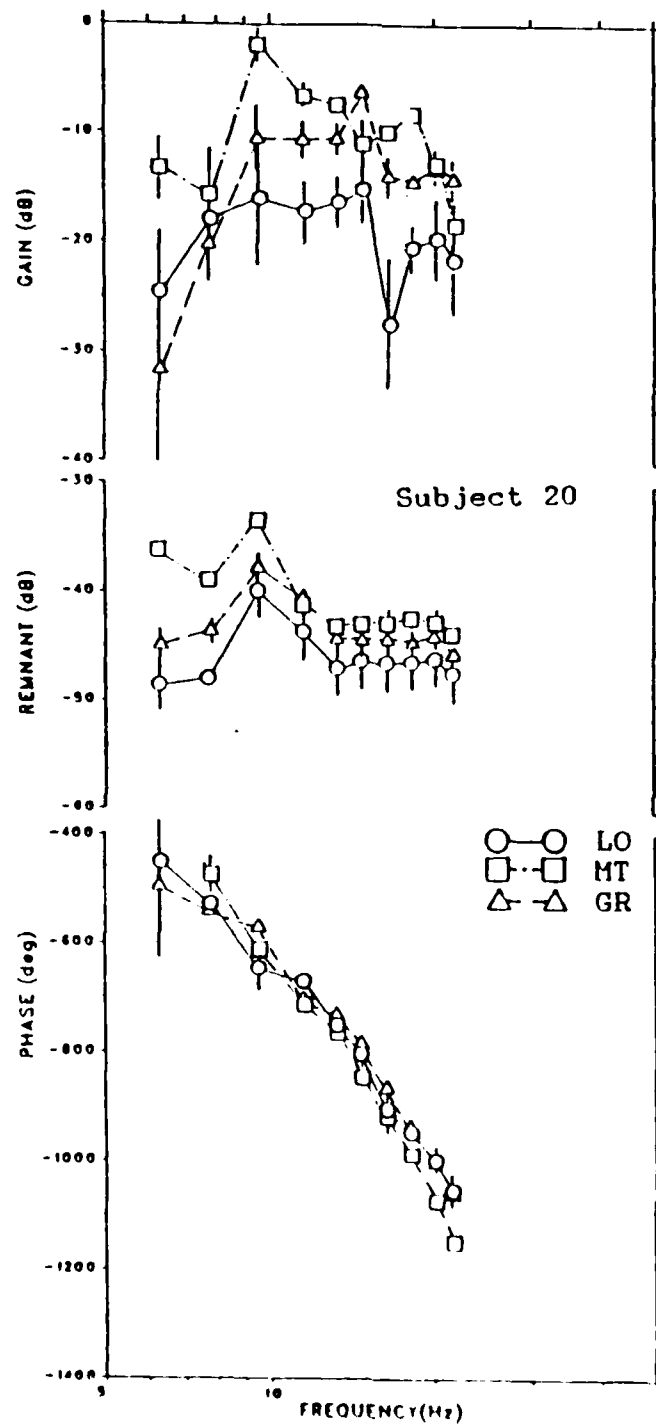
Figure 5.6 (Continued)

condition can be observed. With the addition of Manual Tracking (MT), the alpha peaking decreased slightly. While performing the Grammatical Reasoning (GR) task, the presence of alpha peaking was reduced significantly.

Referring to the gain response curves for Subject 02, a peaking, similar to that observed in the remnant spectra, can be observed for the LO condition. During the GR condition this alpha peak decreased at 9.49 Hz, but not at 11.49 Hz. Of interest is the increase in gain responsiveness for the GR condition in the beta band.

The phase curves for Subject 02 exhibit a flatness between 9.5 Hz and 11.5 Hz which suggests that an additional unwrapping of 360 degrees might have been appropriate. It does not affect the ability to make comparisons across conditions, however. Between 7.49 Hz and 13.25 Hz there is less phase lag for the GR condition as compared to the LO condition.

Due to the behavior of Subject 02 across the three cognitive loading conditions, this subject would be classified as an alpha responder. This behavior is: remnant peak in the alpha band that reduces with cognitive loading, an alpha peak in the gain curve that decreases with task loading, and/or an increase in beta activity in the gain response with cognitive loading. For this subject, differences between LO and GR were more visible than differences between LO and MT.

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5.3.2 Subject 03

Referring next to Subject 03 (Figure 5.6), an alpha like peak can be seen at 13.25 Hz. With addition of MT there was a slight reduction in the peak, and with GR the peak dropped further (although slight). The gain curve exhibits a peak at an even higher frequency of 14.74 Hz. With the addition of GR this peak was reduced significantly. The main effect of cognitive loading, mainly GR and not MT, was less phase lag at the upper frequencies. This subject, loosely speaking, exhibited some of the properties of an alpha responder.

5.3.3 Subject 05

Subject 05 produced an obvious alpha peak in the LO remnant spectrum. With cognitive loading this peak was reduced. The GR task caused the greatest reduction. The gain curve exhibited a corresponding alpha band decrease and a beta band increase with the addition of GR. The phase response indicates that there was less phase lag during the GR condition. Note the last LO and MT phase values, the folding back suggests that another 360 degrees of unwrapping may have been appropriate. Based upon the remnant and gain responses, this subject would be classified a strong alpha responder, much like Subject 05.

5.3 4 Subject 09

No clear alpha-like peak was exhibited in the remnant

spectra of Subject 09. There was little or no change
between the LO and MT conditions. Addition of the GR
condition resulted in an increase in the low frequency
remnant. For the gain response, there was an alpha-like
peak at 13.25 Hz for the LO condition. That is, with task
loading, there was a significant decrease in this peak.
Perhaps this subject had a natural alpha-like resonance at
13.25 Hz, similar to Subject 03, which decreased with task
loading.

5.3.5 Subject 10

Turning next to Subject 10, the first property to
note is the large variability in the data suggesting that
these results may be unreliable. The remnant spectra
exhibited only a slight peak in the alpha band. For the
gain response, with the addition of GR or MT, there was an
increase in the beta band. Associated with this beta
increase was a reduction in the variability of the
response. The phase curves do not present a clear story.

5.3.6 Subject 15

Subject 15 was definitely a non-alpha responder.
There was an increase across the remnant spectrum with the
addition of MT or GR. The same type of increase occurred
in the gain response. There was slightly less phase lag
with the addition of the tasks.

5.3.7 Subject 20

For Subject 20, the excessive variability in the LO data makes it suspect. Thus the focus was primarily on the MT and GR conditions. An alpha peak in the remnant curve can be seen. Going from the MT to the GR condition resulted in a decrease in this peak, similar to what was observed with other alpha responders identified above. The gain curve exhibits the same kind of alpha decrease when going from MT to GR. Finally, there was less phase lag in the GR condition as compared to the MT condition.

5.3.8 Analysis of Task Performance Scores

Average performance scores for the seven subjects tested, including sex and responder type, are listed in Tables 5.14 and 5.15. Model matching parameter values (visual-cortical system "gain" and "delay") resulting from the modeling effort of Section 6.2 are also included.

Turning first to manual tracking performance (Table 5.16), Subject 10 achieved the best performance as indicated by the lowest error score. Subject 15 had the worst performance score. Subjects can be grouped and ranked in the following descending order: Subject 10, 03, 20, then 02, and then 09, 05, and 15. This grouping is independent of sex and responder classification. Comparisons between performance scores and gain-delay model parameter values are worthy of note. The two

TABLE 5.14   Manual tracking performance scores, included
              are modeling results (gain and delay values)
              from Section 6.2.

SUBJ #	SEX	RMS ERROR MEAN	SD	MODEL GAIN	DELAY	RESPONDER TYPE
02	F	1.78	0.40	.151	.169	ALPHA
03	M	1.50	0.07	.338	.108	NON-A
05	F	2.20	0.52	.240	.124	ALPHA
09	F	2.03	0.54	.670	.145	NON-A
10	F	1.32	0.20	.222	.109	NON-A
15	M	2.43	0.51	.135	.126	NON-A
20	F	1.51	0.22	.328	.123	ALPHA

TABLE 5.15   Grammatical reasoning performance scores,
              included are modeling results (gain and
              delay) from Section 6.2 for comparison.

SUBJ	SEX	% CORRECT MEAN	SD	# ATTEMPTED MEAN	SD	MODEL GAIN	DELAY	RESPONDER TYPE
02	F	64	13	15	2	.219	.116	ALPHA
03	M	68	26	10	2	.202	.161	NON-A
05	F	68	12	21	1	.190	.116	ALPHA
09	F	98	4	17	8	.573	.132	NON-A
10	F	69	12	13	2	.255	.108	NON-A
15	M	68	9	12	1	.131	.128	NON-A
20	F	68	10	13	2	.286	.115	ALPHA

subjects with the best performance scores (Subjects 10 and 03) have the lowest delays. The subject with the worst performance score has the lowest gain.

These relationships are encouraging, as the responses are consistent with what would be hypothesized for the visual-cortical portion of a human engaged in manual tracking, namely, that system improvement requires less loop delay. In making these comparisons it must be remembered that the modeling results are for a simple gain-delay model, only seven subjects are considered, and not all subjects reached asymptotic performance levels.

Considering next grammatical reasoning performance scores (Table 5.17), Subject 09 had the highest % correct score. Subject 09 also had the largest gain as determined by the modeling results. In terms of number of two-sentence pairs attempted, Subject 03 had the least. This subject also had the largest model delay.

5.3.9 Summary

In summarizing these results, it appears that the ability to classify subjects as alpha or non-alpha responders would be useful for anticipating and modeling visual-cortical responses. For the alpha responders, the remnant spectra exhibited a decrease in alpha band power with addition of task loading. This was accompanied by corresponding gain changes; a decrease in gain sensitivity in the alpha band, and an increase in the beta band.

Non-alpha responders primarily showed gain changes in the beta band with task loading.

Subjects 03 and 09 would be classified as non-alpha responders because they had no alpha peaks in their remnant spectra. Compared to the other subjects tested, however, they exhibited opposite trends in their gain curves for the LO/GR conditions. This trend was a gain decrease in the beta band with task loading. This decrease is similar to what was exhibited in the alpha band by the alpha responders. Perhaps these low beta band peaks could be classified as high frequency alpha-like peaks. Thus it could be hypothesized that for these subjects, with task loading, these alpha-like peak decreases overshadowed the expected beta increases, as exhibited by the other subjects with task loading.

5.4 Comparisons Across Lights-Only, Manual Tracking and Supervisory Control

Early in the development of the frequency analysis methodology there was an opportunity to collect data from two subjects under three experimental conditions. The conditions were: Lights-Only (LO), Manual Tracking (MT), and Supervisory Control (SC). At the time, it was not possible to obtain remnant measures or ensemble statistics other than mean values for gain and phase. However, in reviewing this data, some interesting trends were observed, consistent with those found in Section 5.3.

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The two subjects performed the three conditions, two times each, at two different sittings, for a total of 4 trials per condition. The EEG data was analyzed using a Nicolet Fourier analyzer as described in Section 4.1.

Describing function results for the two subjects are reproduced in Figure 5.7. Both subjects exhibited alpha peaking in their gain curves, indicative of alpha responders. As noted previously, alpha responders can be expected to show a reduction in their alpha band responsiveness with the addition of cognitive loading.

Looking first at the results for Subject 06, the reduction in alpha peaking for this subject, MT compared to LO and then, SC compared to MT, shows a consistent trend. Less phase lag during SC can also be seen.

Subject 02 did not exhibit an alpha band decrease for the MT condition relative to the LO condition. There was decrease at 7.73 Hz., however. Under the SC condition a large decrease in the alpha band of the gain curve occurred. As with Subject 06, Subject 02 produced less phase lag during the SC condition.

The changes across the conditions of MT and SC are worthy of note. The MT task, once learned, is experienced as a task which requires almost unconscious manual control. The SC task, on the other hand, requires contin-uous decision making on the part of the operator, as to what resources to commit and where. It also demands that more attention be paid to the entire visual field of
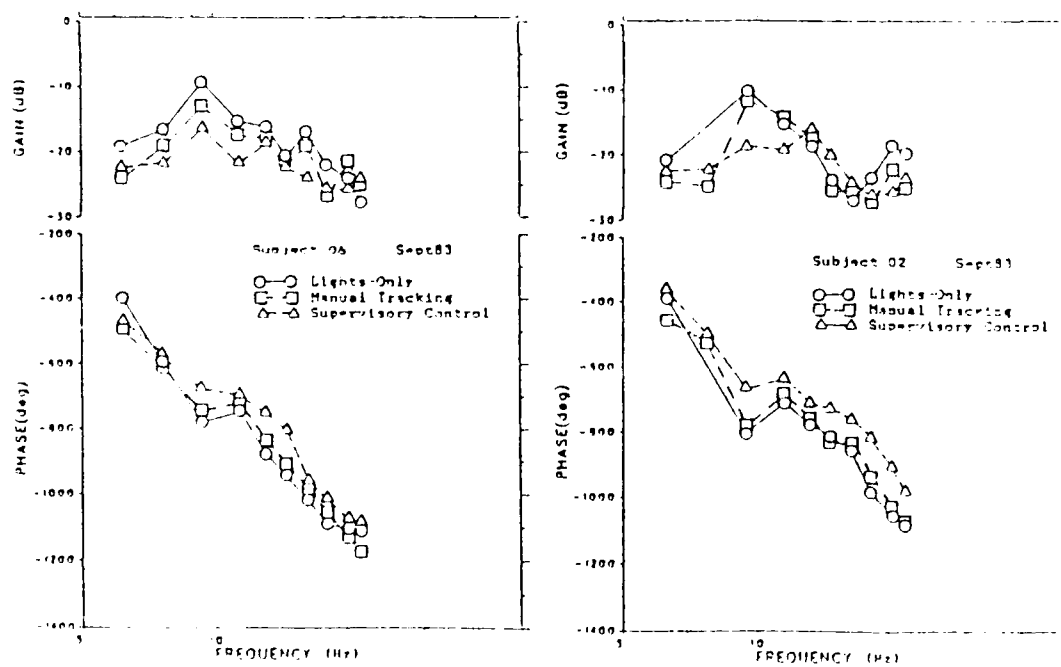
139

Figure 5.7   Describing functions for 2 subjects exposed to
              steady-state stimulation across 3 conditions;
              lights-only as indicated by circles, manual
              tracking indicated by squares, and grammatical
              reasoning indicated by triangles.

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the video display. It can be hypothesized that this added
task loading is reflected in the visual-cortical response
as a decrease in gain in the alpha band and a decrease in
phase lag. Less phase lag can be interpreted as a
speeding up of the visual-cortical system.

It is useful to compare these results to those of
Section 5.3. Subject 02 took part in both studies. Gain
and phase curves are quite similar for this subject for
both studies. The notable difference is that supervisory
control corresponded to a greater alpha band gain
decrease and a greater phase lag decrease than did the
grammatical reasoning task. Perhaps supervisory control
caused more cognitive loading than grammatical reasoning
and is reflected in the describing function differences.

5.5 Supervisory Control Effects, Two Levels of Difficulty

The objective of the work presented in this section
was to determine whether the visual-cortical response
varied systematically with the difficulty level of the
supervisory control task (described in Section 3.4). Two
levels of difficulty were used. In the "easy" condition
it was possible to allocate attention successfully among
the multiple tasks in the allotted time. In the "hard"
condition the average time required exceeded the time
available, and it was not possible to complete all
allocations successfully.

To obtain a better picture of what changes occurred, if any, in each subject's visual-cortical response, describing functions and remnant spectra for each subject were plotted in Figure 5.8. Due to individual differences, each subject is considered separately.

5.5.1 Describing Functions and Remnant, Subject 03

Considering first the remnant curves for Subject 03, it can be seen that there was only a slight alpha-like peak for the LO condition at 13.25 Hz. This compares, somewhat, to results found for this subject in Section 5.3 (refer to Figure 5.6, Subject 03). With task loading, this peak decreased. There was a slight remnant increase in the beta band at 16.49 Hz and above.

The gain curves show a large and significant (Table 5.18) increase in responsiveness for both SC conditions for Subject 03 (Figure 5.8). This is opposite to what was found in Figure 5.6 when the LO condition was compared to the grammatical reasoning condition. It is hypothesized, in view of the lack of alpha response at 13.25 Hz for the LO condition of Figure 5.8, Subject 03 was in an inattentive or fatigued state. Further, that performance of the SC tasks provided a point of focus and required more attentiveness resulting in an increase in the responsiveness of the visual-cortical response as well. Personal communication with the subject confirmed this observation.

The phase curves indicate less phase lag above 13.25

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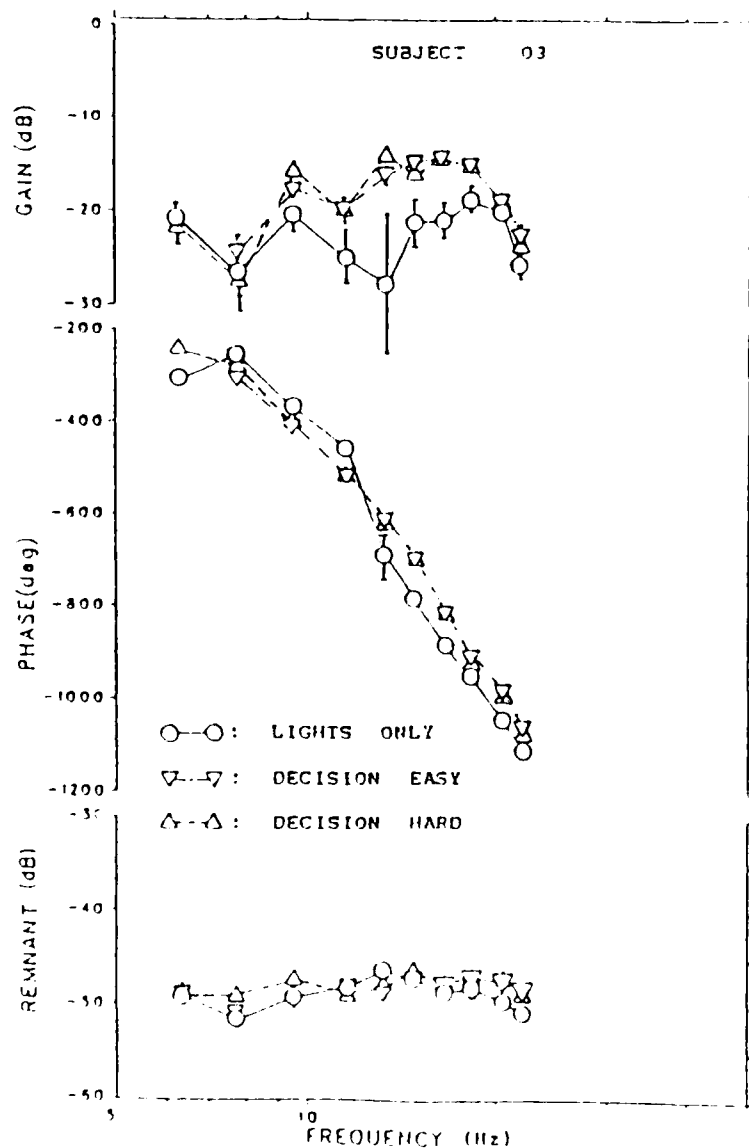
Figure 5.8   Describing functions and remnant spectra for
             subjects exposed to steady-state stimulation
             across 3 conditions; lights-only (circles),
             supervisory control decision making "easy"
             level (inverted triangles), and supervisory
             control decision making "hard" level (up-right
             triangles).

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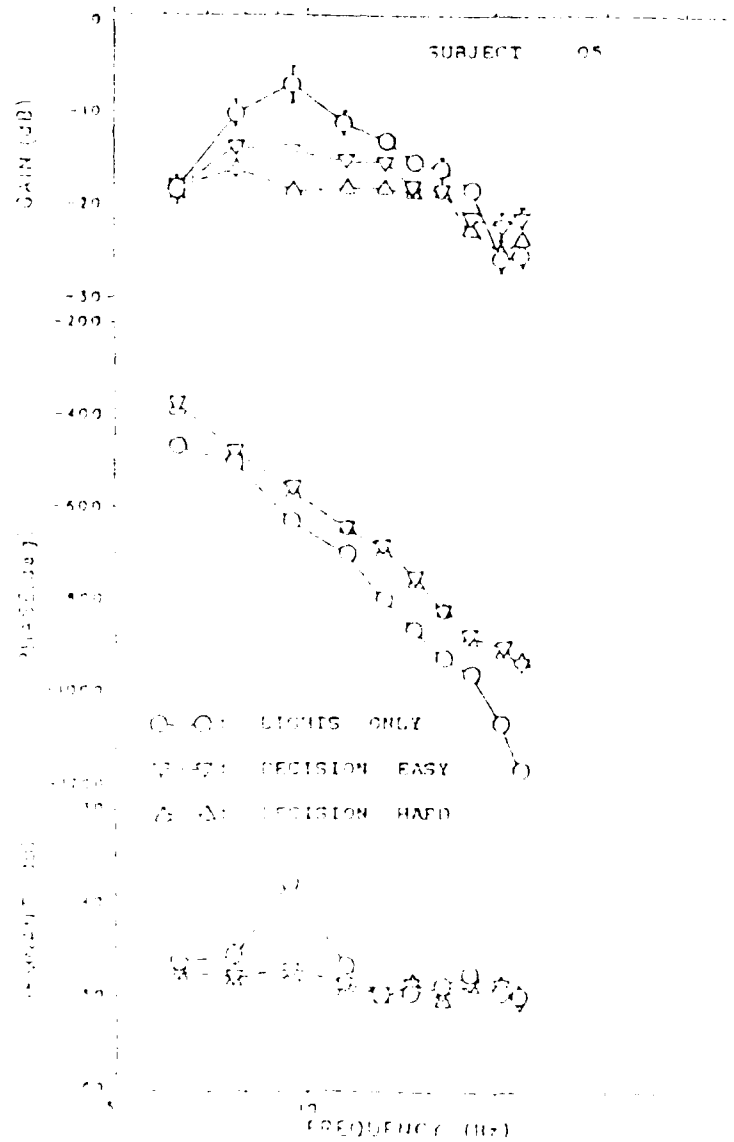
Figure 3-1. (Continued)
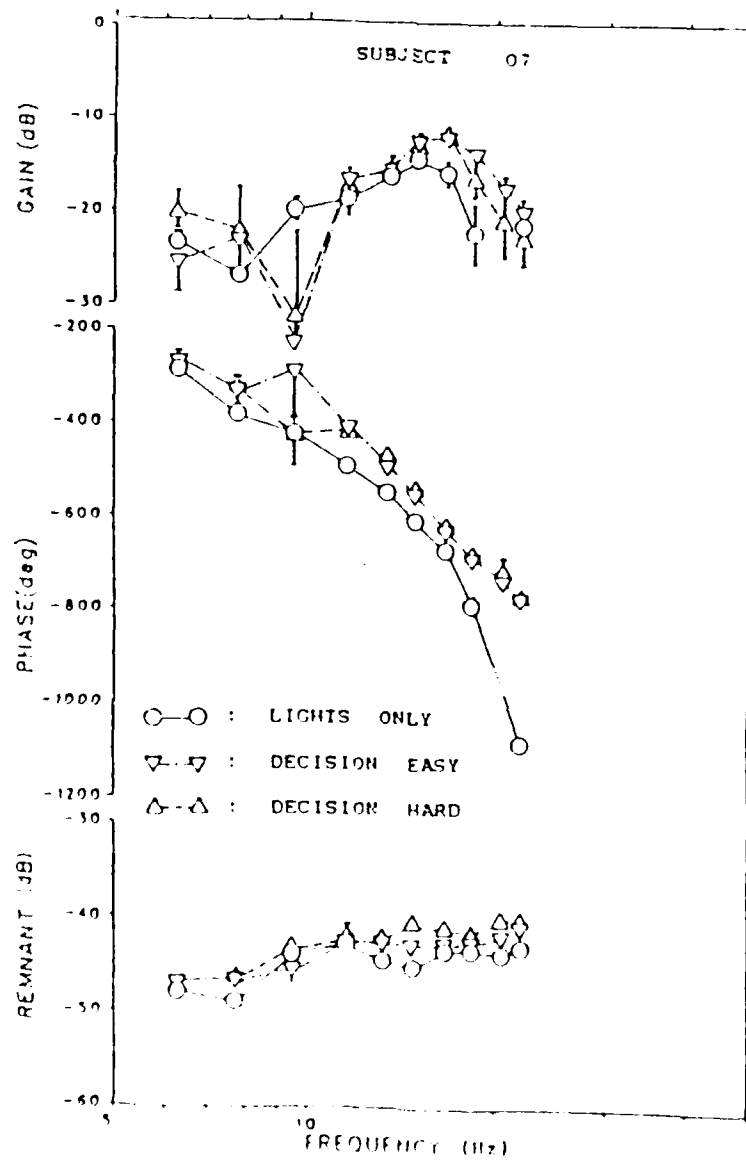
Figure 5 8 (Continued)

145

Figure 5.7 (Continued)

Figure C.8 (Continued)

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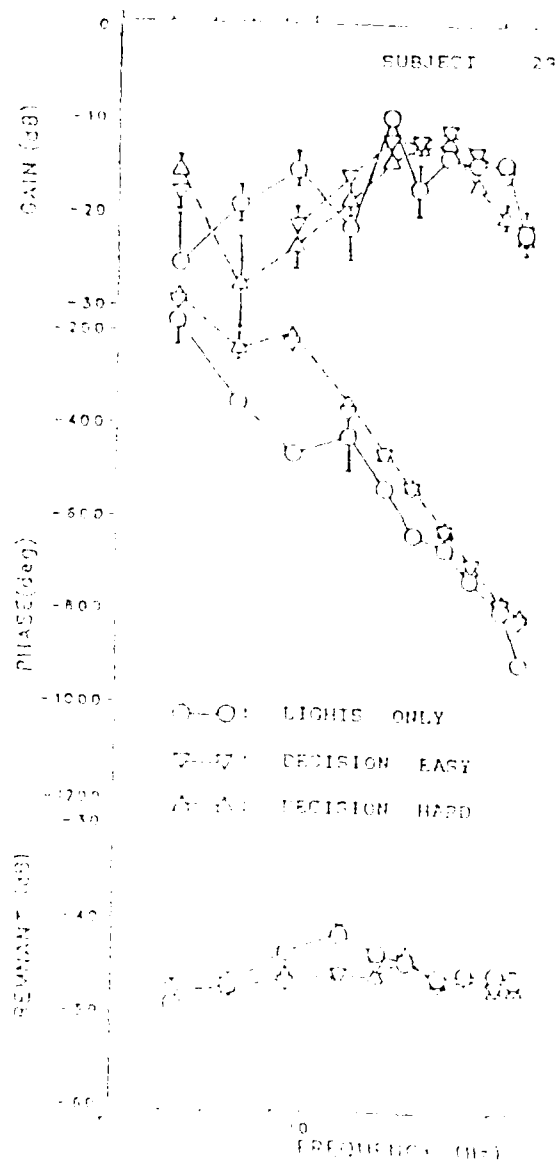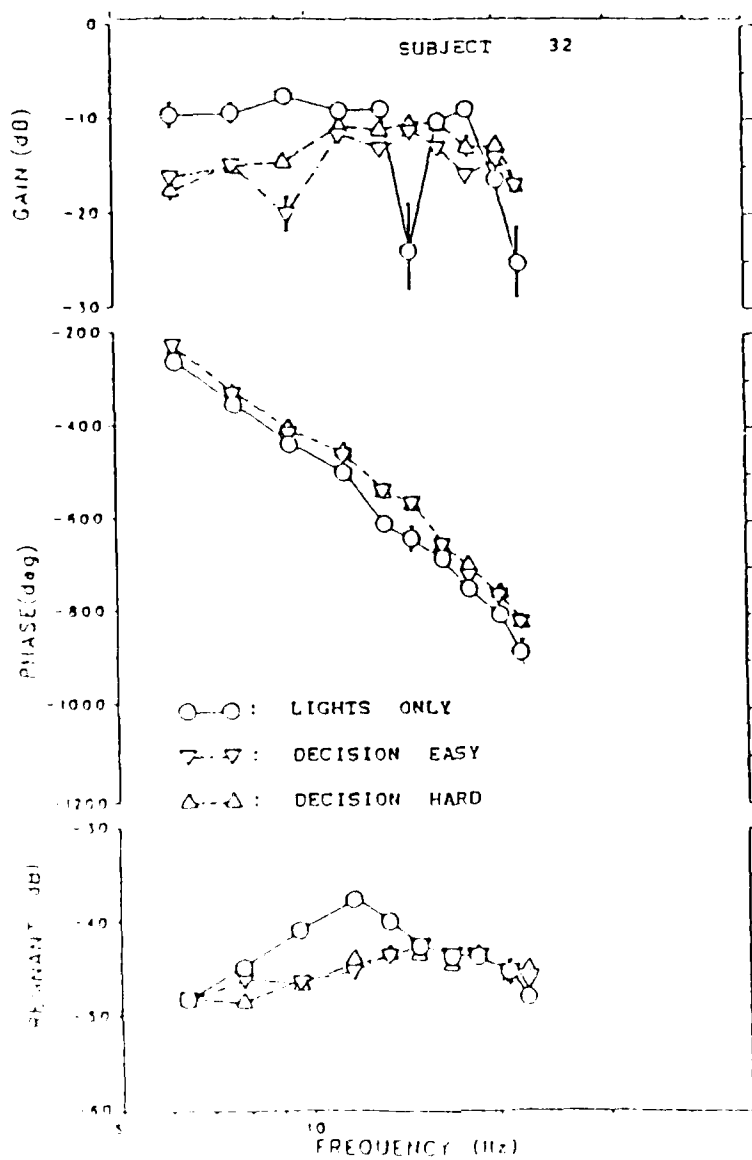
Hz for Subject 03 for both SC conditions relative to the
LO condition At 16.49 Hz, this difference was
approximately 100 degrees. If this difference was simply
due to a reduction in the transport lag of the visual-
vertical system, it would be equivalent to a 16.3
millisecond delay. Furthermore, if in the 14.71 Hz to
16.49 Hz region, the slopes of the phase curves were
considered to indicate the transport lag of the system, it
would equal 158.7 milliseconds for the LO condition
(assuming a zero-order, minimum phase system). Thus, a
16.3 millisecond change from LO to SC would represent a
10.3% decrease in the time delay of the system. The above
these calculations are based simply upon graphical
analysis of the phase data. Future work will require
modeling of the complete describing function data sets.

5.2   Subject 05

Subject 05, unlike Subject 03, had a large alpha peak
in the remnant curve for the LO condition. There was a
reduction in this peak for both SC conditions, with no
significant differences between the hard and easy SC
conditions. Trends here were similar to those observed in
section 5.3 for this subject (Figure 5.6, Subject 05).

There was a decrease in the gain curve responsiveness
from LO to SC easy, and a further gain decrease from SC
easy to SC hard for Subject 05. These changes were
significant between 6.49 Hz and 12.25 Hz. The gain curves

for Subject 05 exhibited a "beautiful" response. If every other subject had such a response, analysis of the visual-cortical response as a measure of cognitive loading would be simple. However, each individual is unique and trends are not so obvious.

Referring to the phase curves for Subject 05, there was less phase lag when either SC condition was performed compared to the LO condition. There were no significant differences between the two SC phase curves.

5.5.3   Subject 07

For subject 07, there was only a slight alpha peaking present at 11.49 Hz in the LO remnant curve. With task loading, instead of this peak dropping, an increase in the beta band occurred. This beta band increase was similar to one observed for Subject 03.

For the gain curves, there was a decrease in responsiveness at 9.49 Hz for the SC conditions. There was, however, an increase in gain at the other frequencies for the SC conditions. The beta band increase was similar to that exhibited by Subject 03. The phase curves for Subject 07 exhibit less phase lag with task loading, much like the curves of Subjects 03 and 05.

5.5.4   Subject 29

The remnant response of Subject 29 exhibited alpha peaking under the LO condition, and an alpha band decrease for both SC conditions. The gain curves for this subject

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also showed a decrease in the alpha band from LO to SC. The presence of either SC condition caused increases in the gain response in the beta band. Less phase lag was also exhibited by Subject 29 under the SC conditions.

5.5.5 Subject 32

Subject 32 had remnant responses quite similar to those of Subject 29. An alpha band decrease with task loading was observed. The gain curve exhibited a decrease in the lower frequency range with task loading. At 14.74 Hz and 21.74 Hz, task loading had the effect of reducing the variability and increasing the magnitude of the gain response. The low magnitude, high variable LO gain responses at these two frequencies are referred to as "dropout" points in this report. They appear to be frequencies at which there was a small or inconsistent response to the evoking stimulus. Much like the other 4 subjects, there was less phase lag present during task loading for Subject 32.

5.5.6 Performance Score Analysis

Table 5.16 lists the average performance scores for the 5 subjects tested. Also included are the sex and responder classification of each subject. Based upon performance scores, subjects can be grouped into two groups: "high" performers (Subjects 29, 07, and 03), and "low" performers (Subjects 32 and 05). For this small

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TABLE 5.16   Supervisory control performance scores.

		% TASKS COMPLETED				
		"EASY" COND.		"HARD" COND.		RESPONDER
SUBJ #	SEX	MEAN	SD	MEAN	SD	TYPE
03	M	82.3	6.5	40.8	6.2	NON-A
05	F	70.0	10.3	33.4	4.2	ALPHA
07	M	84.5	5.5	42.3	5.2	NON-A
29	F	85.2	4.2	40.0	6.1	ALPHA
32	F	76.9	6.2	35.5	3.6	ALPHA

sample of subjects it can be concluded that performance was not based upon classification or sex.

Referring to the gain curves of Figure 5.8, a relationship between performance and gain in the various frequency bands can be observed. For the high performers, gain in the beta band appeared much greater than in the low frequency (alpha and below) range. For the low performers, the alpha-beta gain differences appeared to be much less.

5.5.7 Summary

In summarizing the results of this investigation. Subjects 05, 29, and 32 could be classified as alpha responders. Subjects 03 and 07, on the other hand, would not. All subjects tested produced less phase lag during performance of the supervisory control task. From a systems perspective, less phase lag could be interpreted as a speeding up of a system.

A greater difference in the ratio of gain in the beta region relative to the alpha region was observed for the high performers as compared to the ratio of gain differences for the low performers. Of course, this trend is only for the 5 subjects tested. Future investigations will require a larger sample population.

6. MODELING EFFORTS

The seemingly non-causal nature of electro-cortical potentials, coupled with the lack of reliable theoretical models for the evoked response, limited model analysis to largely atheoretical descriptive modeling. The modeling served two objectives, one of which was to assist in the "unwrapping" of the phase-shift aspect of the describing function data, as described in Section 3.6.4. The second objective was to allow a form of "data compression" by characterizing task loading in terms of changes in a relatively small set of model parameters, rather than in terms of changes in the amplitude and phase-shift measurements (10 each) constituting the visual-cortical describing functions.

6.1 Minimum-Phase Linear Filters

6.1.1 Second-Order Model

Figure 6.1 shows the average gain and phase data obtained from Subject 02 in response to the steady-state lights-only condition. The unmodified phase curve shows upward-directed discontinuities at 7.73, 14.74, and 20.23 Hz. Because the gain curves, for this subject and others as well, had the general appearance of a second-order resonant lowpass filter, a linear model of the following

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6.1a) Phase unmodified
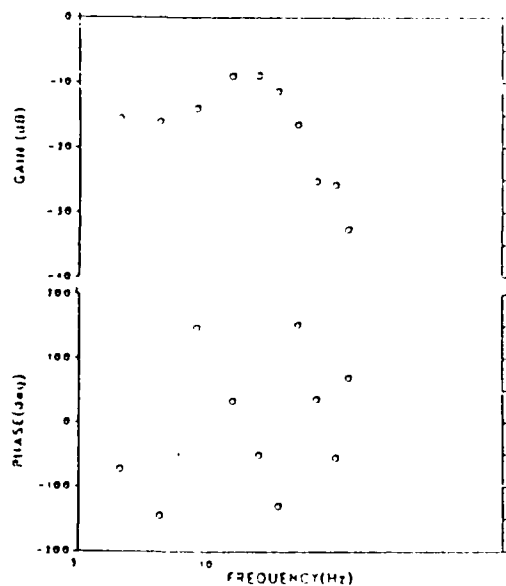
6.1b) Phase unwrapped with descriptive linear model
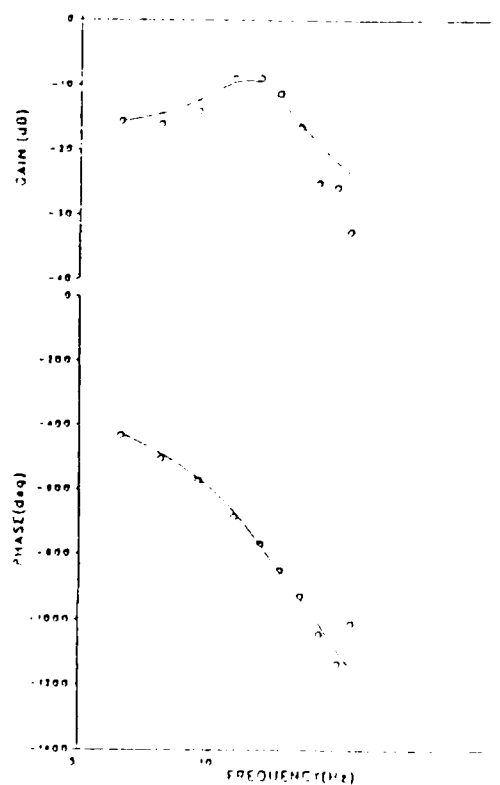
Figure 6.1 Visual evoked response data for Subject 02.

form was employed:

$$F(s) = \frac{K \; Wo^2 \; e^{-sT}}{(s^2 + 2 \; D \; s + Wo^2)} \qquad (6.1)$$

where the four independent model parameters are the asymptotic low-frequency gain K, the natural frequency Wo, the damping-ratio D, and the pure time delay T (the frequency variable "s" is not a model parameter).

An initial selection of parameters was based on the apparent resonant frequency, the asymptotic low-frequency gain, and the difference between maximum and low-frequency gains. In addition, the monotonic and relatively sharp negative increase in phase shift with frequency suggested the presence of a pure delay term, which was also included in the model. The initial estimate of the delay was chosen on the basis of the slope of the phase curve after a preliminary unwrapping in which a 180-degree difference limitation was imposed. When a resonance phenomenon was not apparent in the data, the initial Wo was set to the frequency at which the describing function gain had decreased by about 3 dB from its asymptotic low-frequency value, and D was set between 0.7 and 1.

A scalar model-matching error was defined as the rms difference between model predictions and experimental data, weighted inversely by the standard errors of the experimental data (the unwrapped phase estimates were used for this computation). Best-fitting model parameter values

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were identified using a quasi-Newton gradient search scheme similar to that employed in manual control studies (Lancraft and Kleinman, 1979, Levison, 1983).

Frequency response data were obtained for 4 subjects exposed to steady-state stimulation in the lights-only condition to explore the modeling techniques and to test the phase-unwrapping procedure described above. Data from eight 40.96-second replications were analyzed per subject.

The second-order model of equation 6.1 was fit to the frequency-response data. The quasi-Newton gradient search procedure was employed to iterate on model parameters until the following model-matching error was minimized:

$$
E = \left\{ \frac{1}{2N} \left[\sum_{j=1}^{N} \left(\frac{G_j - \hat{G}_j(p)}{SE_{gj}} \right)^2 + \sum_{j=1}^{N} \left(\frac{PH_j - \hat{PH}_j(p)}{SE_{phj}} \right)^2 \right] \right\}^{1/2} \quad (6.2)
$$

where:

o G_j and PH_j are the average gain and phase estimates for the jth input frequency;

o $\hat{G}_j(p)$ and $\hat{PH}_j(p)$ are the model predictions for gain and phase for a particular choice of values for the model parameters p;

o SE_{gj} and SE_{phj} are the standard errors of the experimental measurements as estimated by the analysis procedure described in Section 3.6.1;

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o   N is the number of input frequencies at which
    reliable gain and phase estimates were obtained.

Model parameters identified by this search procedure,
along with parameter values used for initialization, are
given in Table 6.1. Resulting model "predictions" are
compared with corresponding phase-adjusted experimental
measurements in Figure 6.2. For this analysis, a pair of
gain and phase measurements were considered "reliable" if
the estimated standard error of the gain was less than 2.5
dB. At frequencies where the gain error exceeded this
criterion, gain and phase estimates were omitted from both
the model analysis and from the data plots shown in Figure
6.2. Thus, some of the curves have fewer data points than
others. This analysis validated the procedure outlined
above for unwrapping the phase curve, but it also
indicated that a simple second-order linear model cannot
be expected to provide precision matches to the steady-
state visual-cortical describing functions for all
subjects.

Inspection of Figure 6.2 and Table 6.1 shows that the
quality of the model matches varied across subjects. A
good "eyeball" match to the data in terms of reproducing
important frequency trend (and the second lowest
quantitative matching error score) was obtained for
Subject 09. The good match to the gain and phase curves,

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TABLE 6.1   Model Parameters

	Initialization				Best Fit				
SUBJ	K	T	Fn	D	K	T	Fn	D	E
1	.056	.171	14.7	.369	.085	.141	34.3	-1.27	1.72
9	.100	.056	11.5	.161	.082	.088	11.9	.135	1.52
10	.071	.056	16.5	.111	.114	.070	17.4	.232	1.37
14	.126	.141	9.5	.144	.128	.182	20.5	-1.67	3.27

K = Asymptotic Gain
T = Time delay, seconds
Fn = Natural frequency, Hz
Wo = 2πFn, radians/seconds
D = Damping ratio (dimensionless)
E = Matching error (Equation 6.2)
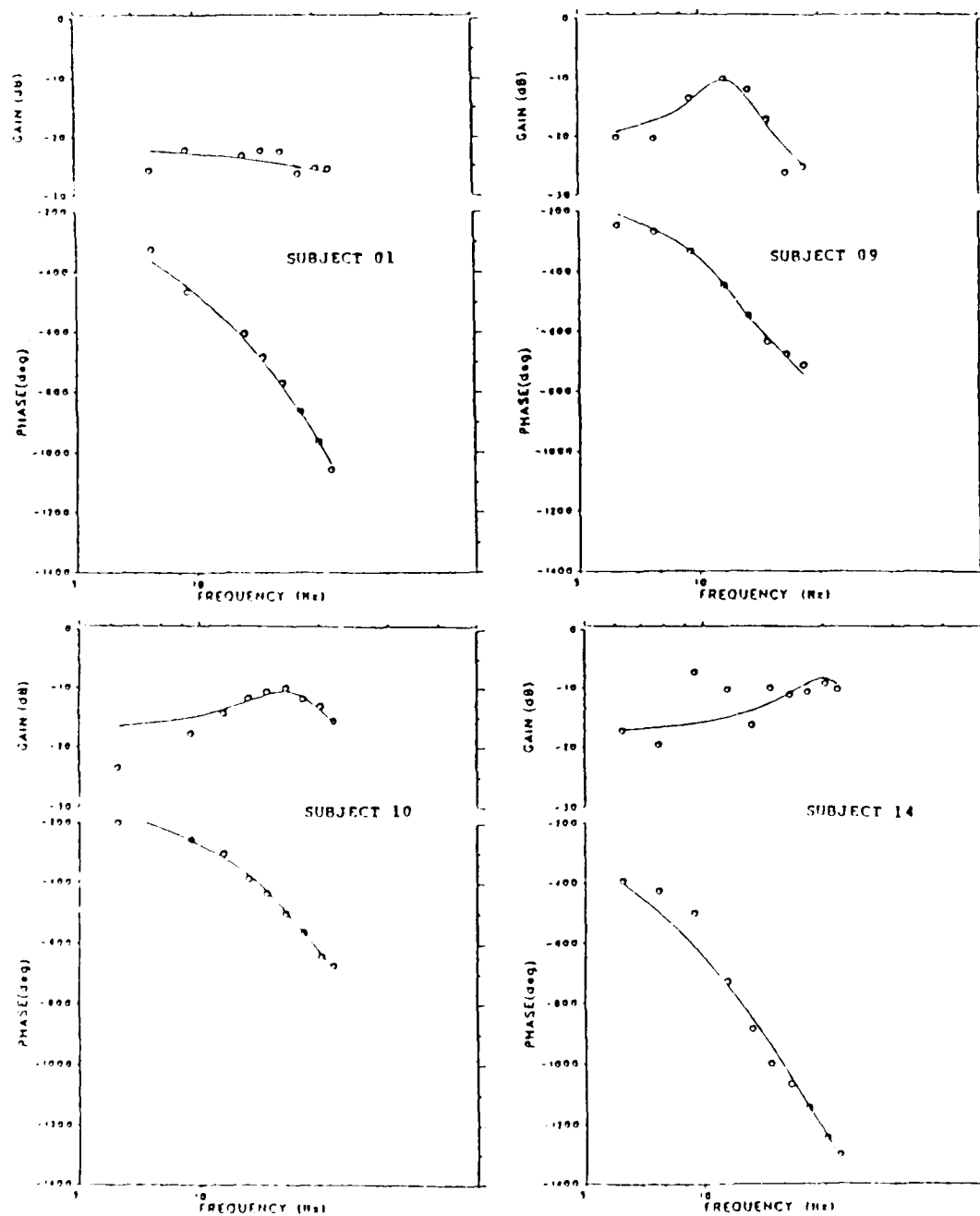
Figure 6.2 Steady-state response, lights-only condition.
Circles represent phase adjusted experimental
values, lines are model predictions.

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coupled with the "reasonableness" of the corresponding model parameters (i.e., parameter values indicative of a dynamically stable system), suggests that the resulting "unwrapped" phase response is valid.

Although data from Subject 10 (Figure 6.2) provided the lowest numerical matching error, the low-frequency "phase droop" exhibited by the data suggest that an alternative model form would be more suitable for matching this particular data -- for example, a bandpass filter (with delay) having both a second-order washout characteristic as well as a second-order high-frequency rolloff. Despite the apparent good match between experimental and model phase characteristics, one would want to obtain a good match to both gain and phase-shift behavior before accepting the results of the phase unwrapping procedure.

Model matching for Subject 01 is another example where there is good qualitative correspondence between experimental and model phase shift, but where the frequency trend of the gain suggests an alternative model form: either a bandpass filter with a relatively large region of flat response, or perhaps a simple gain plus time delay. The negative damping ratio identified from this data set (indicative of an unstable system) casts further suspicion on validity of the model form used.

The least good qualitative match to the data, and the one yielding largest matching error, is for Subject 14.

The multiple peaks in the gain curve suggest that a
higher order filter, or perhaps a model having a delay in
a feedback loop, would be required to provide a good
qualitative match to the experimental data.

6.1.2 Fourth Order Bandpass Filter

Inspection of the data (specifically, the gain curves
of Figure 5.6) suggested that other model forms would more
closely resemble the frequency dependency of the data.
Figure 6.3 shows an example of a data set matched with the
following fourth-order bandpass filter:

$$F = [F1(s) * F2(s)] e^{-sT}$$

(6.3)

where $F1(s)$ and $F2(s)$ are each second order filters

This model was chosen to have four independent
parameters: gain, two natural frequencies, and delay (the
damping ratios were fixed at 0.707).

By constraining the two frequency parameters to be
positive, it was possible to characterize the data with a
stable linear system. Analysis with this model form was
not conducted on a large scale because of the sensitivity
of the results to the initial parameter selection
indicative of local minima), a not uncommon problem when
employing gradient search schemes.
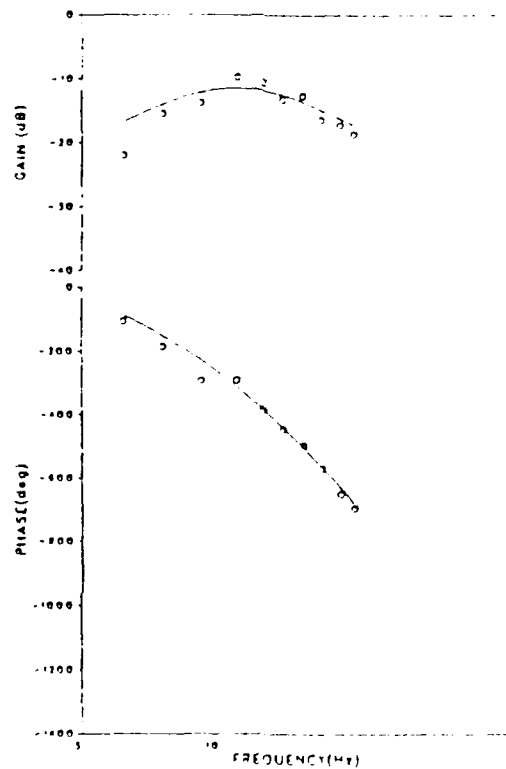
Figure 6.3   Visual evoked response data and model match
using a fourth-order bandpass filter.   Data
is from Subject 02 performing grammatical
reasoning task (refer to Section 5.3).

6.2 Gain/Delay Model

The difficulty of obtaining a consistent model-based characterization of the steady-state describing function data is indicated by inspection of the gain curves shown for two subjects in Figure 6.4. This data is taken from Section 5.3. For the lights-only (no-task) condition, the data for Subject 02 (Figure 6.4a) resemble the frequency response of a resonant lowpass filter, whereas the data for Subject 03 (Figure 6.4d) resemble an inverted "v" and are perhaps modeled by a tuned bandpass filter.

The curves for the tracking condition (Figures 6.4b and 6.4e) show no consistent effects of task loading: the data from Subject 02 reveal regions of diminished response, whereas the data from Subject 03 show less of a qualitative change from the baseline. For the grammatical reasoning condition, however, both subjects showed gain response curves that appeared to vary less with frequency than the baseline. Specifically, the presence of the grammatical reasoning task seemed to "flatten" the gain curve, compared to the baseline lights-only condition.

This observation led to the testing of the gain/delay model. This model had the form:

$$F(s) = K\ e^{-sT} \qquad (6.4)$$

where K and T are the "gain" and delay parameters.

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a) Subject 2, No Task

d) Subject 3, No Task

b) Subject 2, Tracking

e) Subject 3, Tracking

c) Subject 2, Reasoning

f) Subject 3, Reasoning

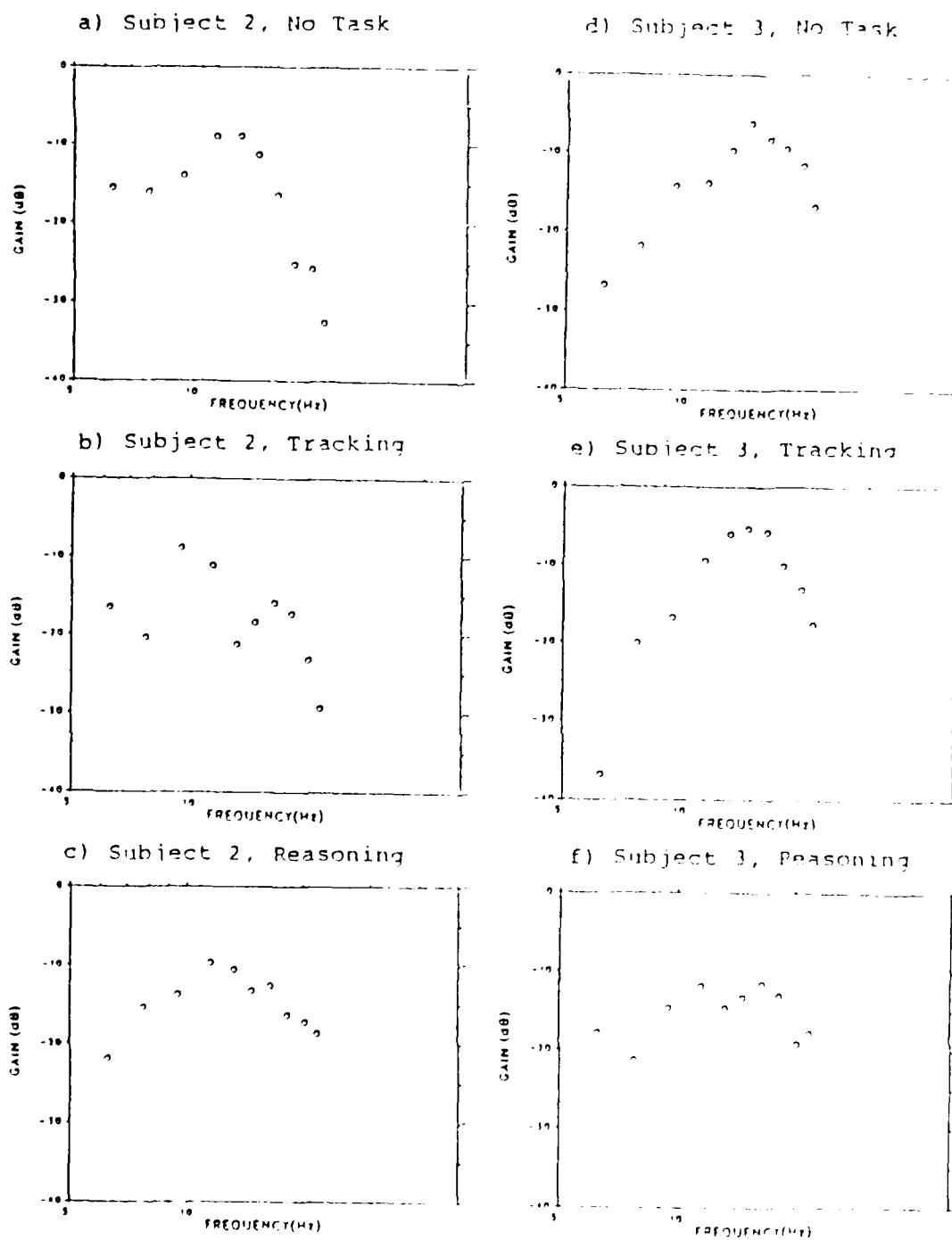Figure 6.4   Effects of task loading on the visual-cortical
evoked gain response.

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Parameters were obtained for each experimental trial.
The results of this matching effort are presented in a
subject-by-task format in Table 6.2. The unwrapped phase
data resulting from this data set was used in Section 5.3
for investigating the effects of task loading. Fitted
model parameter values were used for comparison with task
performance scores (refer to Section 5.3.8).

To determine the consistency and significance of the
"flattening" effect, the modeling results of Table 6.2
were collapsed across subjects. These average results are
listed in Table 6.3. On the average, the gain/delay model
provided the best match (i.e., least matching error) to
the describing function data corresponding to the
grammatical reasoning task condition, and the least good
match to the tracking-related data. Both the gain and
delay parameters showed lowest values for the lights-only
(no-task) condition and largest values for the manual
tracking condition. Task-related differences in the three
parameters were generally small, however. Paired-
difference t-tests failed to reveal any task effects
having an alpha significance level less than 0.05. This
analysis, therefore, fails to support the hypothesis that
task loading influences the relative "flatness" of the
frequency response for all subjects. The lack of signif-
icance is not surprising based upon the observed individ-
ual differences exhibited in the data of Section 5.3.

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TABLE 6.2 Results of the Gain/Delay model match to
describing funtion data.

Lights-Only : LO
Manual Tracking : MT
Grammatical Reasoning : GR

SUBJ	CONDITION	GAIN	DELAY	ERROR
2	LO	0.150	0.113	3.99
	MT	0.151	0.169	5.37
	GR	0.219	0.116	3.01
3	LO	0.261	0.112	4.75
	MT	0.338	0.108	6.54
	GR	0.202	0.161	2.79
5	LO	0.213	0.127	3.71
	MT	0.240	0.124	3.05
	GR	0.190	0.116	2.05
9	LO	0.683	0.131	3.35
	MT	0.670	0.145	1.57
	GR	0.573	0.132	1.74
10	LO	0.209	0.108	1.76
	MT	0.222	0.109	2.08
	GR	0.255	0.108	3.17
15	LO	0.115	0.131	4.06
	MT	0.135	0.126	3.98
	GR	0.131	0.128	3.39
20	LO	0.121	0.118	0.96
	MT	0.328	0.123	2.96
	GR	0.286	0.115	2.41

TABLE 6.3 Results of Gain/Delay model match to describing
function data, collapsed across subjects.

	GAIN		DELAY		ERROR	
COND	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
LO	0.250	0.198	0.120	0.010	3.23	1.36
MT	0.298	0.182	0.129	0.021	3.65	1.78
GR	0.265	0.610	0.125	0.018	2.65	0.61

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6.3 Multipath Model

As noted in Section 6.2, task loading appeared to have the effect of flattening the frequency dependency of the gain curve for some subjects. In some cases, curves having an appreciable frequency dependency also showed "dips" or "dropout" points at one or more frequencies. The standard errors of the gain measurements at these minima tended to be substantially greater than the standard errors at other frequencies (see Subject 02, Figure 5.6; Subject 32, Figure 5.8).

These observations motivated the search for a consistent model form for which a variation in one or more parameters would exhibit similar behavior. The following simple multipath model was constructed to replicate the general trends described above:

$$F(s) = K1 \, e^{-sT1} + K2 \, e^{-sT2} \tag{6.5}$$

where K1 and K2 are constants ("gains")
and T1 and T2 are pure time delays.

The visual-cortical response is thus represented as the summation of unfiltered signals arriving at the recording site via two pathways having different attenuation and different transit times. This model reflects the notion that surface electro-cortical recordings measure the cumulative effects of multiple

deep-seated events conducted to the cortical surface by multiple pathways, and that cognitive processing will influence the particular pathways involved at any given time.

A small effort was undertaken to determine model parameters, and parameter changes, that would replicate the observed trends. Qualitative trends were replicated by varying the gain parameter $K2$, with the remaining three parameters fixed. On the basis of the effective delays identified in the test of the gain/delay model, $T1$ was set at 0.12 seconds. $T2$ was set at 0.187 seconds to provide a maximum multipath cancellation effect (a dip) at 7.5 Hz. $K1$ was set at -0.2 to provide a baseline gain on the order of that found experimentally, and $K2$ was treated as the independent parameter of this analysis.

The model reverts to the simple gain/delay form (no frequency shaping) for $K2 = 0$. Figure 6.5a shows a modest frequency dependency for $K2 = -0.05$. For $K2 = -0.10$ a local minimum appears in the gain curve at the second input frequency (7.73 Hz), and the gain curve at higher frequencies exhibits the appearance of an inverted U (Figure 6.5b). Figure 6.5c shows this trend to be more pronounced as the magnitude of $K2$ is further increased ($K2 = -0.15$). Visual comparison of the three sets of model predictions reveals that the variability of the gain response across varying $K2$ is greatest at the frequencies (7.73 and 21.74 Hz) at which local minima occur.
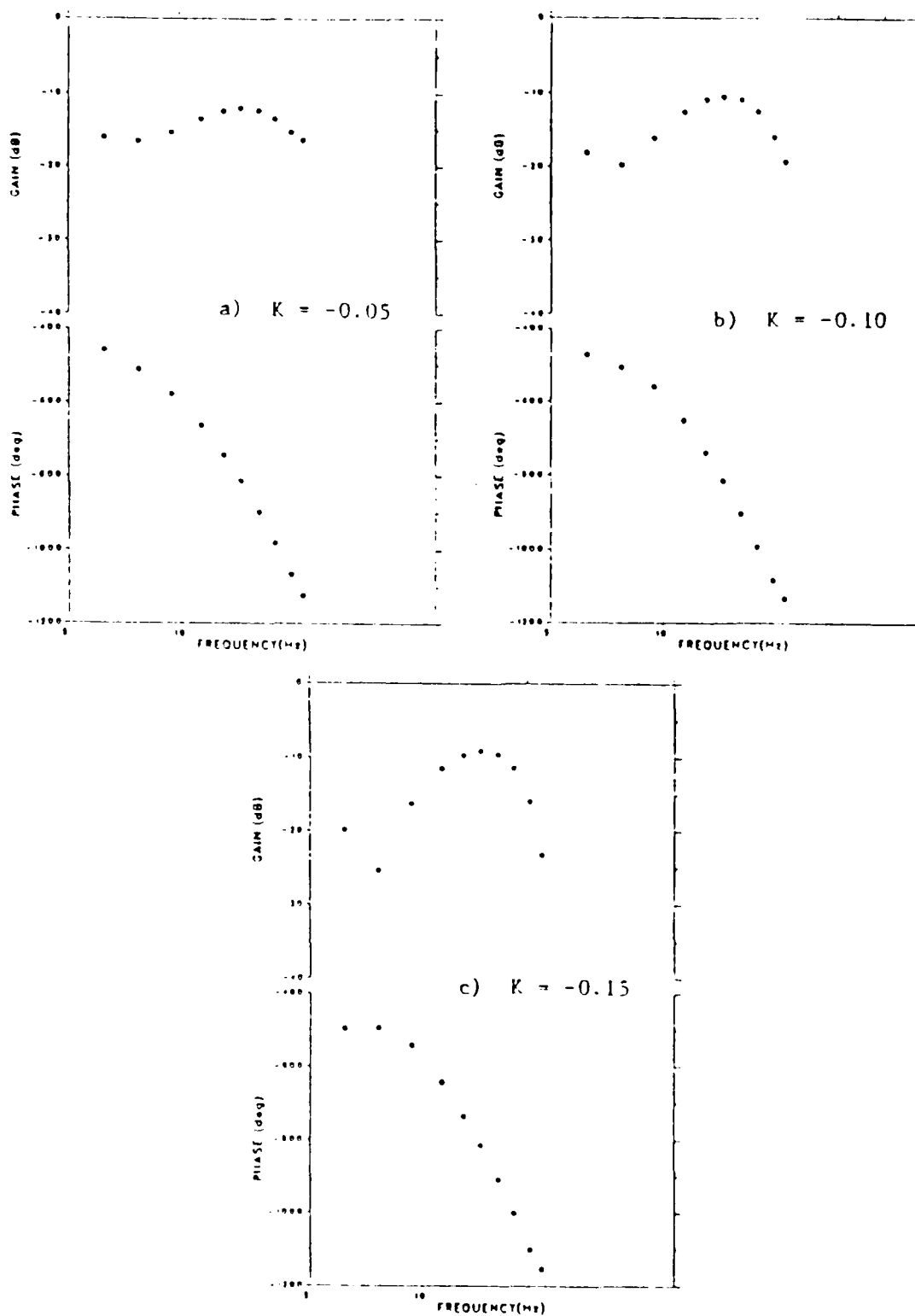
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Figure 6.5   Sensitivity analysis of multipath model,
effects of gain on K2.

This multipath model is thus able, with a single parameter change, to vary the frequency dependency of the gain curve from no dependency at all (flat curve) to one that exhibits a general inverted-U shape with a dip at one of the lower measurement frequencies. Furthermore, the sensitivity of the predicted describing function gain to model parameter variations is greatest at frequencies exhibiting the local minima, which is consistent with the experimental findings that these local minima showed the largest variability.

6.4   Summary of Modeling Results

Three model forms were explored in an attempt to develop a parsimonious characterization of the visual-cortical response.   Linear dynamic filters were first explored, both low-pass and bandpass.   While such model forms were able to provide a reasonable qualitative match to the data, the appropriate model form appeared to vary across subjects and sometimes across tasks.   Parameter variations did not follow a clear trend, and model parameter values were not always consistent with a stable response mechanism.

A simple gain/delay model was explored next.   This model was used as the basis for phase unwrapping.   It provided a means for testing the hypothesis that task loading tended to "flatten" the frequency of the gain

component of visual-cortical describing functions. It also provided a convenient mechanism for exploring potential relationships between task loading and response delay. No statistically significant relationship between task loading and model parameters was found, and the hypothesis that loading tends to flatten the response across subjects was not supported.

Finally, a study was performed to explore a simple model based on the notion that surface electro-cortical recordings measure the cumulative effects of multiple deep-seated events conducted to the surface by multiple pathways. Further, that cognitive processing will influence the particular pathways involved at any given time. Preliminary testing of a model containing two paths, each consisting of an attention and a delay, showed that manipulation of a single model parameter could replicate some of the differences observed among the visual-cortical frequency-response plots.

CONCLUSIONS AND FUTURE POSSIBILITIES

Work on a new systems engineering based methodology
for investigating human electrocortical responses has been
presented   The methodology has been developed by using the
human visual-cortical response channel for access into the
human system.

This methodology can now be utilized for further
research into human brain function. The contribution of
this work comes from providing procedures and postulates
for future studies. The procedures developed are:
appropriate sum-of-sines stimulus generation, approaches
for specifying stimulus intensity and depth of modulation,
analysis techniques, modeling approaches, and rules for
subject classification. Postulates relating to the
effects of task loading and attention levels have been
formulated.

To develop the methodology, areas considered were: 1)
stimulus impact on the EEG, 2) relationships between
steady-state and transient modes of stimulation, 3) the
effects of task loading on the EEG, and 4) modeling of the
steady-state describing functions.

This section summarizes the research findings which
have led to the realization of the objective of this work.
The ways in which these findings correlate with prior
research are presented   Consistencies and discrepancies

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are noted   Future research possibilities are discussed
where appropriate, including an approach for achieving
loop-closure of the visual-cortical channel.

7.1 Stimulus

It was found that subjects respond to the Sum-Of-
Sines (SOS) stimulus (see Figures 4.1 through 4.4).   It
was further observed that the response could be measured
quite accurately (within a 0.0244 Hz band), and that
coupling or confounding effects due to spontaneous EEG
resonance near the evoking frequency could occur.
Repeatability of the measure was also observed.

Investigation into the effects of stimulus parameter
characteristics is perhaps best summarized by Figures 4.8
and 4.9.   For the subjects tested, the evoked response
frequencies of greatest sensitivity were between 9.49 Hz
and 18.25 Hz.   Two areas of obvious sensitivity were the
alpha band and beta band.   For the lowest level of
modulation and intensity, and thus stimulus power, a
strong response was evoked at 9.49 Hz and a not so strong
(but obvious) response occurred at 16.49 Hz.   Increasing
the depth of modulation to 13%, with the intensity
unchanged (40 ft-L), resulted in the largest evoked
response and a flattening in the correlated EEG power
spectrum (11.49 Hz to 14.74 Hz).   At 13% modulation,
increasing the intensity further (to 80 ft-L) succeeded

only in producing a slightly noticeable increase in the evoked response at 16.49 Hz. This high level of intensity and modulation actually resulted in the smallest evoked response at 9.49 Hz.

As can be seen in Figure 4.9, the remnant responses were only mildly affected by the different stimulus parameter values. The statistical results of Table 4.4 support this observation.

These results indicate that the evoked response is a function of frequency as well as stimulus strength. These findings correspond to others reported in the literature (refer to Section 2.4.1). What was not reported elsewhere was the fact that saturation across frequencies was unequal. The alpha region was the most sensitive, so saturation could occur quite easily. The results also indicated that individual differences were significant, and that they must be considered for a more complete picture of visual-cortical functioning.

From the results, it can be concluded that the lower level of intensity and higher level of modulation provide the better stimulus parameter values. In designing a stimulus, it would be best to choose values which cause minimal distraction of the tasks being investigated. An intensity level of 40 ft-L was adequate for the experimental paradigm investigated for this report.

The fact that remnant was unaffected by the evoking stimulus and that an alpha coupling was observed suggests

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that it is best to consider both remnant and evoked response together.

The investigation of stimulus parameters points to future research possibilities. Tailoring the stimulus spectrum to each individual as a function of their evoked response sensitivity may produce more reliable visual-cortical responses.

7.2 Transient/Steady-State Stimulation

The two modes of stimulation produced comparable results (refer to Figure 5.4). Time-locked average amplitude reductions, due to task loading, corresponded to describing function gain decreases. Large amplitude peaks, characteristic of a "ringing" system, related to large alpha peaks. The time domain response shifts, from lights-only to grammatical reasoning, were similar to results reported in the literature.

An important observation was that responses were unique to each individual, but comparable across modes of stimulation. Similar responses imply stimulation of the same visual-cortical mechanism. Differences in responses were also observed (refer to Figure 5.5) related to levels of attention. These findings indicate the need for considering each subject individually, and the importance of accounting for the subject's state of awareness.

This could best be done by taking a systems approach

to analysis of the EEG data. Considering only the transient amplitude components in the time domain does not provide a complete picture. Describing functions, obtained from transient stimulation, furnish useful phase unwrapping information. Steady-state stimulation, on the other hand, provides both describing function and remnant information. Furthermore, the input can be concentrated at only a few frequencies. Stimulation with both inputs is advisable for a more complete picture of the visual-cortical system. If performance, time locked to an event, is desired, transient stimulation might be best. If a continuous measurement over time is needed, steady-state stimulation is suggested.

Task effects resulted in both N100 and P300 changes, similar to results reported elsewhere (refer to Section 2.4.2). An interesting finding reported by other researchers and not found in the data reported in Section 5.2 were the independent responses in N100 and P300. The N100 component is reported to be affected by stimulus relevancy, and the P300 is reported to exhibit reduction with increasing perceptual processing demands. The tasks explored in this thesis required both attention to a visual stimulus and increased perceptual processing. It might prove useful to investigate a task which requires only increased perceptual processing and no attention to a visual stimulus, such as mental arithmetic. If this caused P300 changes, and no N100 changes, ways in which

these changes mapped to frequency domain describing
functions would perhaps provide useful insights into the
functioning of the visual-cortical system.

7.3 Task Effects

Significant changes in visual-cortical measures
across tasks were observed (refer to Section 5). These
changes were specific to each individual tested. The
differences in subject responses suggest that it would be
useful to group subjects into at least two groups: alpha
responders, and non-alpha responders. Determination of
how to group each subject would be based upon alpha band
resonance or peak responses for remnant and gain. With
task loading, subjects with alpha decreases in both the
remnant and gain response would be classified as alpha
responders. Non-alpha responders would be characterized
primarily by a beta increase in gain and remnant with task
loading.

Gain curve changes corresponded to remnant changes in
the alpha band for subjects classified as alpha
responders. In the beta band (above 13 Hz) the gain curve
activity appeared to be independent of the measured
remnant for most subjects tested.

Different effects upon the visual-cortical response
were observed for the three tasks investigated. Manual
tracking had the least effect for most subjects, and

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grammatical reasoning and supervisory control had the most. Results indicated that the more mental processing required, the greater the alpha band decrease and the greater the beta band increase. In the supervisory control mode, a consistent reduction in phase lag in the beta band was observed for all subjects tested (refer to Figure 5.8).

The two levels of difficulty of the supervisory control task produced similar results. There were only a few frequencies at which there were likely to be significant differences between difficulty levels. These frequencies, which varied across subjects, indicate locations where future investigations of task loading might be focused. This is further considered in Section 7.5.

The results of Sections 5.3.8 and 5.5.7 suggest the possibility that task performance may correlate with visual-cortical response frequency measures. Thus model parameterization may provide predictive information regarding a subject's ability to perform a particular task.

In the Appendix it was reported that, with appropriate awareness and training, physical activity with eyes open could be accompanied by high alpha and low beta activity. This was an opposite trend as compared to what was observed for task loading in Section 5. These findings suggest an interesting area for future research. Perhaps the state of relaxation and degree of training,

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during performance of a task, could be studied via EEG alpha band and beta band monitoring.

7.4 Modeling

Describing function data was modeled using various linear model forms. Results of the second-order model match (Figure 6.1) indicated that a good match could be achieved for some subjects and not others. The fourth-order form tested was too sensitive to starting values. The simple gain-delay model was useful as an aid in phase unwrapping. However, it did miss some points where a further unwrapping of 360 degrees was called for (refer to Figure 5.6). The multipath model results indicated an approach to account for the "dips" or points of large variability found in the describing function data.

Due to individual differences, it will be necessary to tailor the form of the model used to each subject. Perhaps by grouping subjects into two groups, two general model forms would be sufficient to compress the visual-cortical response data into a more parsimonious format.

7.5 Future Possibilities, Loop-Closure of the Visual-Cortical Response

The results of this research effort indicate that describing functions can be obtained, and that they are sensitive to changes in task loading. It was also found

that the results are unique to each individual. Further it was found that the results are sensitive to attention, especially in the alpha band.

These results are promising, however there is one difficulty with this measure, and perhaps with most evoked physiological measures, that needs to be addressed. The visual-cortical response is an open loop measure. Unlike manual control, where an optimal behavior for best performance exists, the subject is not provided with an environment directing a certain response

In the lights-only condition, subjects were told to "look at the lights". No feedback relative to how well they were responding was provided. Even with this lack of feedback or loop closure, the evoked response was seen to be repeatable (refer to Figure 4.10). Of course, this "repeatability" is strictly a within-subject attribute, which does not hold across subjects. Variability due to attention shifts were also observed (Figure 5.5). Task loading often reduced response variability and improved measurement reliability. Even so, subjects were often unaware of their state of attention, resulting in a weak or unevoked response.

Based upon what was learned from manual control experiments, it is concluded that the solution to improvement of the visual-cortical response measure is to develop a closed-loop visual-cortical response paradigm. This will require providing an appropriate feedback signal

to the subject.

From the evoked response data it was observed that evoked potentials could exhibit frequency responses as narrow as the measurement bandwidth (refer to Figure 4.3). Thus frequency specificity of the feedback signal should be of concern.

If a feedback loop is to be effective it must also contain minimal transport delays. EEG biofeedback trainers at the Menninger Foundation (personal communication) indicated that a biofeedback signal should not be delayed more than 4 cycles for it to be a useful signal from which subjects could learn to "control" their EEG.

From the above discussion, it is concluded that for the feedback signal to be effective it must be both timely and frequency specific. Useful feedback information about a 20 Hz response, for example, might require no more than a 0.05 second delay. To achieve this small delay and simultaneous frequency specificity is not an easy task. For the work reported here, a frequency specificity of 0.0244 Hz was achieved, but only by analyzing 40.96 seconds of data at a time. Thus it is concluded that frequency resolution and timeliness can not be achieved by digital means. Instead, an analog active-filter approach is suggested.

The approach recommended involves using a tuneable bandpass filter in combination with a Lock-in Amplifier System (LAS). A diagram for this system is presented in
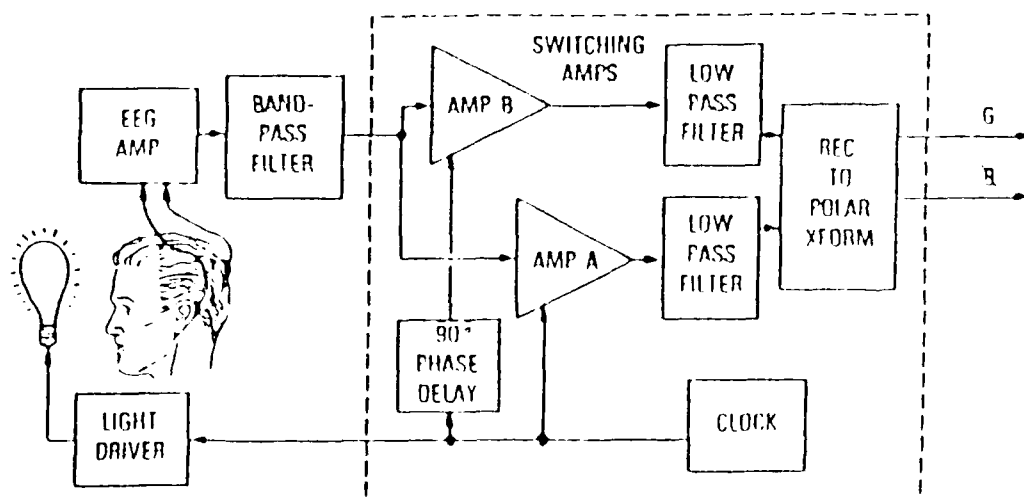
Figure 7.1   Lock-in amplifier system.
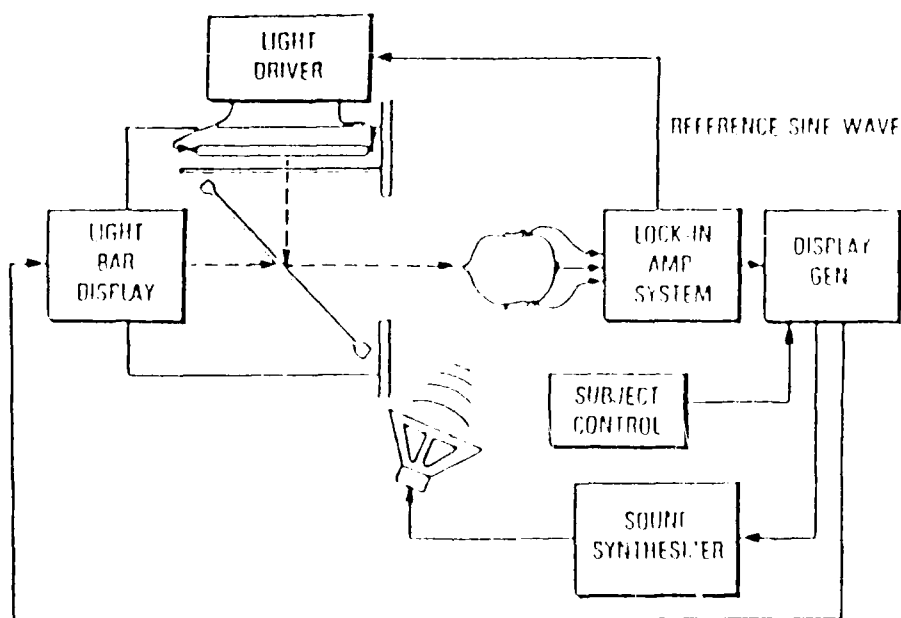

Figure 7.2   Possible experimental setup for feedback
            training.

Figure 7.1. The LAS consists of two quadrature phase sensitive detectors, the outputs of which are lowpass filtered and converted to polar form to yield continuous gain and phase signals at the lock-in frequency. The lock-in frequency is determined by a clock which generates a square wave, a quadrature square wave, and a sine wave. The square waves drive amplifiers A and B. The sine wave is used to drive the light stimulus. The bandpass filter (tuned to the clock frequency) is used to improve the signal to noise ratio of the signal analyzed by the LAS. The responsiveness and frequency specificity of the LAS depends upon the cutoff frequency of the lowpass filters.

The LAS provides a continuous measure of gain and phase suggesting an immediate application. It could be used in conjunction with steady-state stimulation to explore the time varying nature of task loading. The approach would be to stimulate with the SOS stimulus, and during stimulation, continuously record the LAS output at one of the 10 SOS frequencies. Preselection of the frequency to monitor could be based upon statistical data such as reported in Table 5.18. The continuous measure could be correlated with the time varying nature of the task. In the case of the supervisory control task this might be: times of appearance of new targets, or times before or at the moment of button pushing.

The above is still an open loop measure. To begin to close the loop, it will be necessary to provide feedback

to subjects of their EEG production at specific frequencies. A possible experimental setup to accomplish this is illustrated in Figure 7.2. Feedback of EEG production is provided to subjects through two modes; a light bar display, and an amplitude modulated tone. The tone could be chosen by the subject to be a "pleasing" vibration, or it could be chosen to be harmonically related to the reference sine wave at which the subject is to learn EEG control.

As configured in Figure 7.1, the LAS may be too slow in responding or not sufficiently frequency sensitive to provide an effective feedback signal. Certainly for large amplitude or large phase variations in the EEG at the reference frequency this will be true. For small perturbations, once a feedback loop has been achieved, LAS response time may be sufficient.

Widening the lowpass filters improves LAS response time, but widens the LAS bandwidth. A possible improvement to the LAS, in the form of a phase locked loop, may be possible. In a typical phase locked loop the reference frequency is made to follow the phase of the incoming signal for system stability. For this application, it will be necessary to use feedback to "encourage" the human to follow the phase of the clock signal as a method of stabilizing the loop. Utilizing analog delay lines to shift the phase of the reference sine wave as it drives the light stimulus may achieve the

desired effect. The approach would be to delay the sine wave one complete cycle and lead or lag an additional amount, determined by the phase signal of the LAS. Another possibility would be to recreate the EEG signal only at the reference frequency, as determined by the LAS, with appropriate phase lead to drive the evoking stimulus. The intention of these approaches would be to provide a better evoking stimulus so that the visual-cortical system knows it is "looking at itself".

With appropriate loop closure, humans may be able to achieve narrow-band frequency control of their brain waves. This ability could lead directly to control of brain-actuated systems.

Considering the neurophysiology of the brain near the surface (Guyton, 1976), the cortex is rich in dendritic connections. This evokes the image of a sensitive radio receiver/transmitter (Figure 7.3). Perhaps in the future a direct connection through microwave sensing (Tourenne, 1985) will be used for brain-actuated control. At this time, however, the technology presented can help to open the way, while providing insight into the workings of the human brain and the beginnings of mental-state estimation.

BRAIN WAVES

Figure 7.3 Brain Waves, illustration by
Robert Paschell, 1985.

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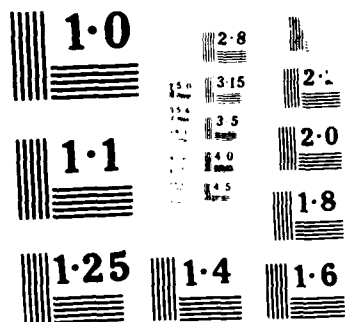
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